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CONTENTS

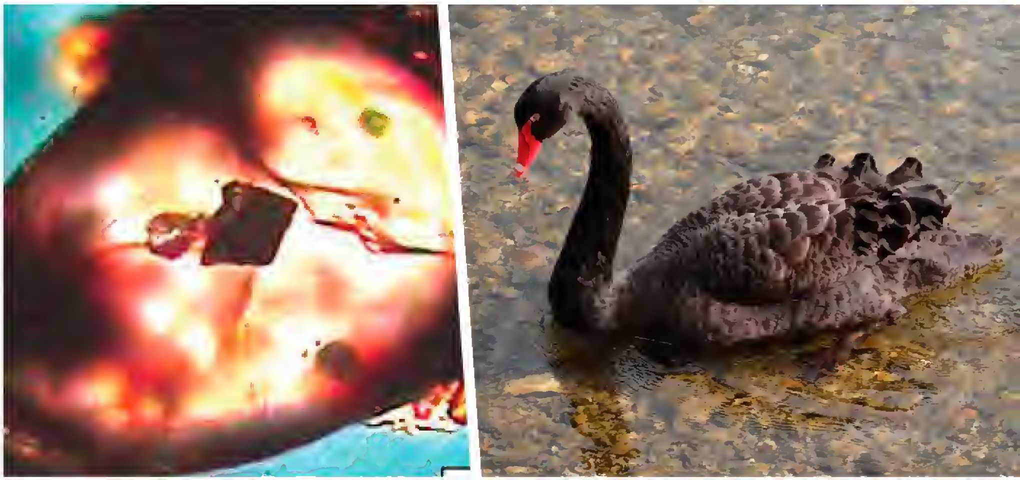
PREFACE i

Archaeological assessment of coastal and marine development sites: case study from James Price Point, Western Australia
I Ward, P Larcombe, A Carson & A Lane 31

Hydrological change at Lake Clifton, Western Australia – Evidence from hydrographic time series and isotopic data
M Forbes, R Vogwill 47

Middle Permian (Roadian) Foraminifera from mudstone facies of the type Baker Formation, Southern Carnarvon Basin, Western Australia
D W Haig, A J Mory 61

Referees 76



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PREFACE

Many readers of the Journal will be pleased to see the return of earth science papers to its pages. David Haig and Alfred Mori's paper on Foraminifera from the Middle Permian of the Southern Carnarvon is particularly welcome.

The Royal Society of Western Australia, in the tradition of the Royal Society of London, prides itself in being an interdisciplinary science organisation, and its Journal is always open to papers which touch on more than one of science's disciplines. The very topical paper by Ingrid Ward and her colleagues on the archaeological assessment of a submerged development site in northern WA – that of James Price Point touches on geology, sedimentology, climate history and bathymetry as well as archaeology.

In a similar way, the paper by Matthew Forbes and Ryan Vogwil utilises a conceptual framework that depends on hydrology, climate history and ecology in an evaluation of the effects of recent environmental changes to Lake Clifton, Western Australia.

All three papers provide readers with examples of the application of modern techniques to assist in the understanding of Western Australia's environment.

P H Armstrong
Editor-in-Chief

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Archaeological assessment of coastal and marine development sites: case study from James Price Point, Western Australia

I WARD [1*], P LARCOMBE [2], A CARSON [3] & A LANE [4]

[1] *School of Social Sciences, University of Western Australia, WA 6009 Australia*

[2] *RPS MetOcean Pty Ltd., Jolimont, WA 6008 and School of Earth and Environment, University of Western Australia WA 6009, Australia*

[3] *Western Australia Museum, Welshpool, WA 6106, Australia*

[4] *C/- Piers Larcombe at RPS MetOcean Pty Ltd., Jolimont, WA 6008, Australia*

* *Corresponding author* ✉ *ingrid.ward@uwa.edu.au*

Abstract

This paper examines the prehistoric marine archaeological potential of relict shorelines off James Price Point, northern Western Australia. In addition to previously registered midden and intertidal fish-trap sites, archaeological excavation at James Price Point has provided evidence of coastal exploitation from at least 5 ky BP. In the adjacent marine environment are well-preserved drowned shoreline sediments, that form at least two series of north - south trending linear features with relief of up to 5 m of more above the surrounding seabed, at elevations of - 15 m and - 8 m respectively, which may date to ~ 9 ky BP and ~ 6 ky BP respectively. The submerged shorelines are associated with four main depositional environments, of which, 'lagoon infill' and 'fossil intertidal flats' have the highest preservation potential and highest archaeological potential. This palaeogeography has significant geoheritage value and systematic investigation of these features is likely to contribute to our understanding of early maritime adaptation and resource use in this region.

KEYWORDS: submerged landscapes, palaeoshorelines, geoheritage, prehistoric marine cultural heritage, James Price Point

INTRODUCTION

The Archaeological Potential of Submerged Areas

With the rapid expansion of marine industrial developments in many regions of the globe, a key challenge is to maximise the opportunities for research to support collaborative monitoring and management of known and potential archaeological sites (Evans *et al.* 2009; Firth, 2015; Flemming 2004; Ward *et al.* 2014a). In Australia there has been little conceptual or practical understanding of the potential impacts of marine development activities (e.g. ports and harbours) upon the largely unknown prehistoric marine resource. Further, the limited statutory framework for marine prehistoric cultural resources means the need for research is even more acute (Kamoot 2014; Staniforth 2007). This major knowledge gap in submerged cultural potential is perhaps most apparent off Western Australia where some of the biggest marine developments are occurring and where we now have some of the oldest records of coastal occupation, extending back some 50,000 years (Veth *et al.* 2014; Veth & O'Connor 2013).

Information from drowned sedimentary deposits can provide valuable information about past environments, past sea levels and associated past cultures (Bailey 2014; Benjamin *et al.* 2011; Flemming 2004). Models designed to examine the potential archaeology of submerged landscapes include theoretical (Chapman & Lillie 2004; Fischer 2004) and technological approaches (Gaffney *et al.* 2007; 2009; Mahon *et al.* 2011; Webster 2008). Geoarchaeological approaches use the associations between different landforms and different types of archaeological and/or environmental remains (e.g. Howard and Macklin 1999; Rapp and Hill 1998) to estimate of the potential presence of submerged archaeological deposits (Gagliano *et al.* 1982; Ward and Larcombe 2008). This in turn has lead to the development of Indicative Maps of Archaeological Potential or Values (IMAP; Deeben 2009). Such maps are used to indicate those specific areas of the coastal and marine zone interpreted as having relatively low, medium or high potential for the presence of archaeological remains in primary and secondary depositional contexts, i.e. in situ or re-deposited (see also Cohen *et al.* 2014; Ward & Larcombe 2008). Delineating boundaries within IMAPs requires assessment of both the nature of the depositional environments as likely sites of occupation and/or concentrations of archaeological artefacts (Deeben 2009), together with consideration of any post-depositional modification processes (Rowland & Ulm 2012; Ward *et al.* 2015).

Embedded within the established regional geoarchaeological understanding (Ward *et al.*, 2013, 2014b, 2015), this paper applies a geomorphically-based approach to assess the archaeological potential of a small (15 km x 40 km) submerged area off northwest Australia, namely the former gas hub development area of James Price Point, near Broome, on the southern Kimberley

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coast. This assessment is necessarily based on an interpretation of (i) the available geological, bathymetric and sedimentary data, including the past and present sedimentary processes and (ii) existing archaeological information, including the known and likely past human use of terrestrial and coastal environments both of which are outlined below. The aim of this assessment is to show the considerable potential for prehistoric marine heritage with the potential to address specific questions of early maritime adaptation (Ward *et al*. 2014b; 2015), and where to focus any future research efforts.

GEOLOGY, BATHYMETRY AND SEDIMENTOLOGY

Regional setting

The continental shelf fringing northwestern Australia forms an expansive shallow marine environment with a tropical to sub-tropical oceanographic regime, rich carbonate production and low terrestrial sediment supply. In the region of James Price Point, the shelf is broad (100 – 250 km), has relatively low relief and grades gently into the upper slope at depths of 100 – 150 m (Picard *et al*. 2014). Throughout the Pleistocene, the Leveque Shelf and adjacent North West Shelf (Figure 1) have been subject to long periods of sub-aerial exposure at low-stands of sea level. During the Last Glacial Maximum (LGM), sea level in region was 100 – 130 m lower than present, and most of the shelf would have been emergent (Lewis *et al*. 2013; Yokoyama *et al*. 2000). The prolonged low-stand conditions during the LGM appear to have formed a shelf-wide terrace backed by a 30 m high ridge, now located ~125 m below sea level (James *et al*. 2004). Representing the ancient coastline, this ridge is clearly evident on bathymetric surveys of the North West Shelf (WAMSI 2008).

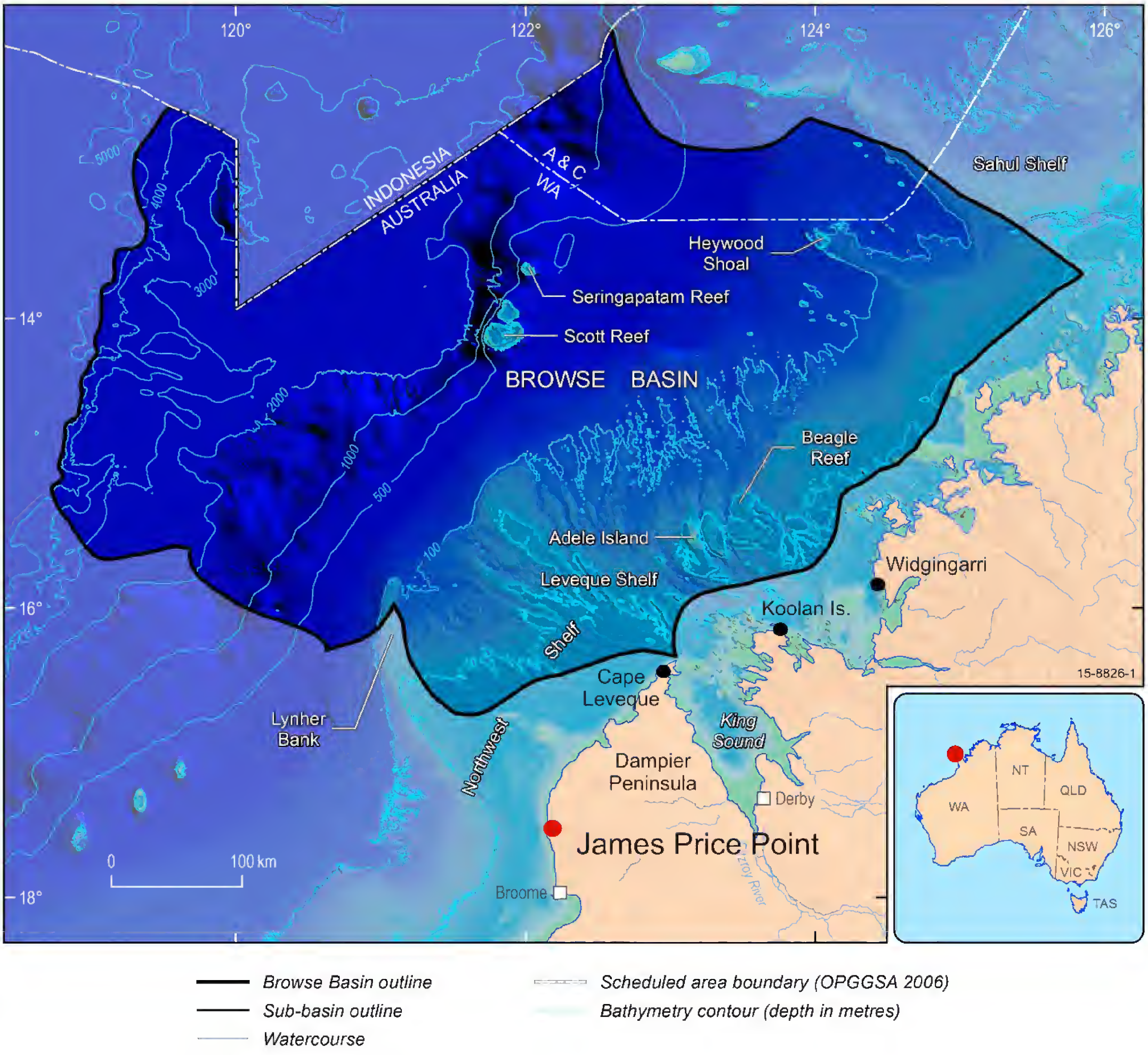


Figure 1. Map of Browse Basin and Leveque Shelf (© Commonwealth of Australia, Geoscience Australia 2015. This product is released under the Creative Commons Attribution 3.0 Australia Licence. http://creativecommons.org/licences/by/3.0/au/deed.en).

Modern sedimentary processes on the continental shelf include transport by fast tidal currents and episodic cyclone-associated flows (Collins 2011). Coastal areas bordering the Leveque Shelf host strong, semi-diurnal tidal currents, and maximum tidal ranges over 10 m (Picard *et al.* 2014). The Kimberley region experiences frequent tropical lows, with an average of three per year (Lough 1998) producing strong onshore winds, enhanced wave energy and storm surges that influence the coastal geomorphology (Elliot & Elliot 2008). Despite this, undisturbed archaeological material both on and behind the cliff-top at Cape Leveque indicate long periods of stability (> 800 years) at least on some parts of this Kimberley coast (Barham & O'Connor 2007).

James Price Point (JPP)

The coastal geomorphology at James Price Point is characterised by a mixture of narrow beaches and rocky shores, with intertidal reef platforms of lithified coastal sediments, small spits and coastal dunes driven by the prevailing south-westerly winds, and adjacent Holocene terrestrial dunes (Eliot & Eliot 2008). To the south, these features give way to low-lying coastal dunes (Shoonta Hill sand; Semeniuk 2008), whilst to the north lie eroding cliffs of red sand (Mowanjum Sand; Semeniuk 1980), locally termed 'Pindan' (Lowe 2003). There is little fluvial sediment supply to James Price Point or the wider area, but wet-season rain drains across the coastal ridges and foredunes to the ocean through narrow ephemeral channels (Eureka 2010; Kenneally *et al.* 1996) or as subsurface seepage under the Mowanjum Sand (Mathews *et al.* 2011).

At JPP, the intertidal zone is generally rocky (predominantly coastal limestone) with patches of reef and wide (< 1 km) areas of intertidal sand flats, with weathered Broome Sandstone exposed in places at very low tides. The subtidal zone is generally shallow, with a complex configuration influenced by a series of exposed cemented relict shoreline features, scoured sub-tidal channels and fields of large, albeit low mobile, south-facing sand waves (Figures 2– 4). The seabed sediments are generally sands of mixed terrigenous and biogenic composition, with carbonate content increasing offshore. Re-deposition occurs through regular transportation by strong, shore-parallel tidal currents. Measured in 34 m of water off JPP, spring tidal current speeds regularly attain 0.55 m/s near the bed and 0.8 m at the surface (RPS MetOcean 2012). Closer to shore, in 18 m of water, near-bed currents are typically 0.5 – 0.55 m/s at spring tides and able to mobilise the sandy sediments. During cyclones, current speed can be greatly enhanced. During Cyclone Laurence (December 2009), in 18 m of water, peak flows attained >1.15 m/s at the surface and 0.92 m/s near the bed, flowing to the south and south-south east along the shelf. Under these flow conditions, much of the seabed would have been in transport, redistributing much shell midden material and small stone artefacts, whilst less mobile stone tools might be buried below sand.

Seabed sedimentary features are key to understanding the geological setting and features, and the Holocene evolution of an area, and necessarily underpin an assessment of archaeological potential. Recent information on the North West Shelf (e.g. Hengesh *et al.* 2011, 2012; Picard *et al.* 2014) contributes to regional knowledge. High-resolution survey data, including Light Detection and Ranging (LiDAR) data (Figure 2) indicates the presence of an array of submerged features (Figure 3). Together with available information on the sedimentary sequences and the coastal geology (DSD 2010a; 2010b; Eliot & Eliot 2008; GSWA 2009; Semeniuk 2008), this helps to delineate four main types of sedimentary deposits or features as a useful basis for assessing prehistoric marine archaeological potential. These are:

- Coastal Limestone – relict reef, probably dating from the last interglacial (Marine Isotope Stage 5, MIS 5). (Figure 2, and labelled as 'nearshore rock' in Figure 3).
- Palaeoshorelines – A series of coast-parallel features, including cemented carbonate dune and coastal deposits. The two main fossil shorelines (Figure 2) are here referred to as the -8 m and -15 m shorelines, relating roughly to mean sea level (MSL), to allow relatively easy comparison with the bathymetric datasets and images (MIS 1/2).
- Fossil Intertidal Flats – smooth and low-gradient areas landwards of the outer palaeoshoreline (Figure 2).
- Lagoon Infill – an infilled shore-parallel basin between the coastline and -15 m palaeoshoreline (labelled 'Marine Sands' in Figure 4) containing sediments up to 11 m thick (MIS 1/2).

EXISTING ARCHAEOLOGICAL INFORMATION

Regional archaeological context

Early Aboriginal occupation on the west Kimberley coast is documented *at Widgingarri 1* (from c. 50 ky BP) on the mainland (Veth & O'Connor 2013) and Koolan Shelter 2 in the Bucaneer Archipelago (from 27.3 ky BP, O'Connor 1999). The presence of shellfish remains and shell artefacts dated to between 28 – 26 ky BP at these sites indicates early exploitation and use of marine resources by Aboriginal people (O'Connor 1999; Veth & O'Connor 2013). Between 10,000 and 7,000 years ago, as coastlines and islands formed following sea level rise, previously abandoned rockshelter sites were re-occupied and new coastal sites occupied for the first time (O'Connor 1999). This rapid settlement of new coastlines and islands indicates that people had been living along the Pleistocene coast with well-developed maritime economies and following the rising sea (O'Connor 1999).

A mid- to late Holocene sequence of dated middens and cheniers from Cape Leveque to Roebuck Plains indicates continuing Aboriginal occupation of the coastal zone through 6,000 years of coastal progradation (O'Connor & Sullivan 1994; Smith 1987; 1997). South of Broome, shell middens yield dates between 3 and 1 ky BP (O'Connor and Veth 1993). The presence of flaked glass and historical material at a number of sites indicates that occupation of these places continued at least until the contact period and beyond (O'Connor & Veth 1993).

Archaeological sites on the Dampier Peninsula are concentrated on the resource-rich coastal margins,

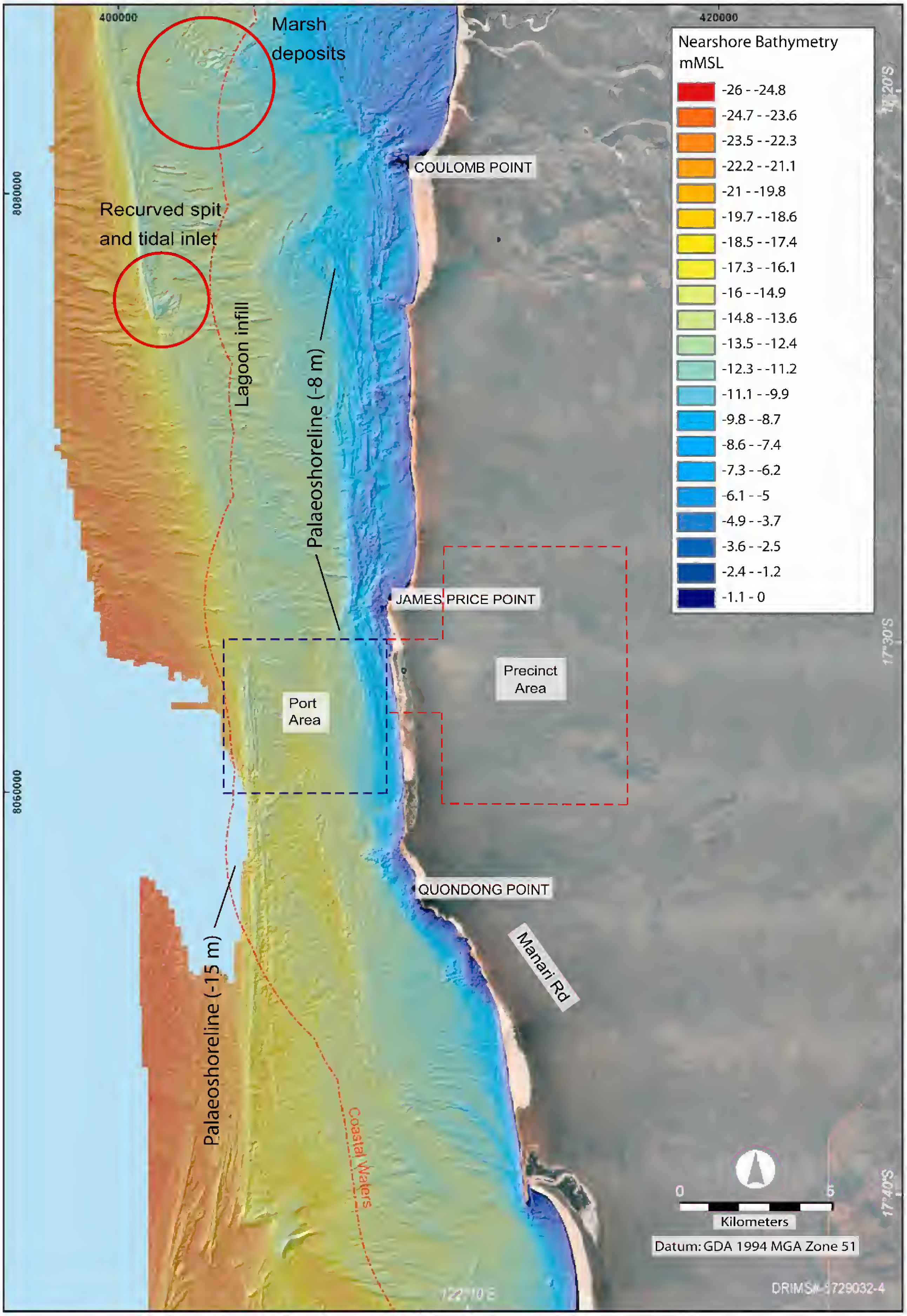


Figure 2. Surface topography and nearshore bathymetric image off JPP, showing detail of: left – the series of parallel N-S lineations of the -15 m shoreline; centre – the relatively flat smooth sea bed of the 'lagoon', and; central right – the NW-SSE shore-parallel lineations of the -8 m shoreline. The modern shoreline shows a rocky low intertidal zone, active upper beach, active and vegetated dunes, and blowouts. The Mowanjum Sand or 'Pindan' plain is located immediately to its landward (from DSD 2010a, Fig.1–8).

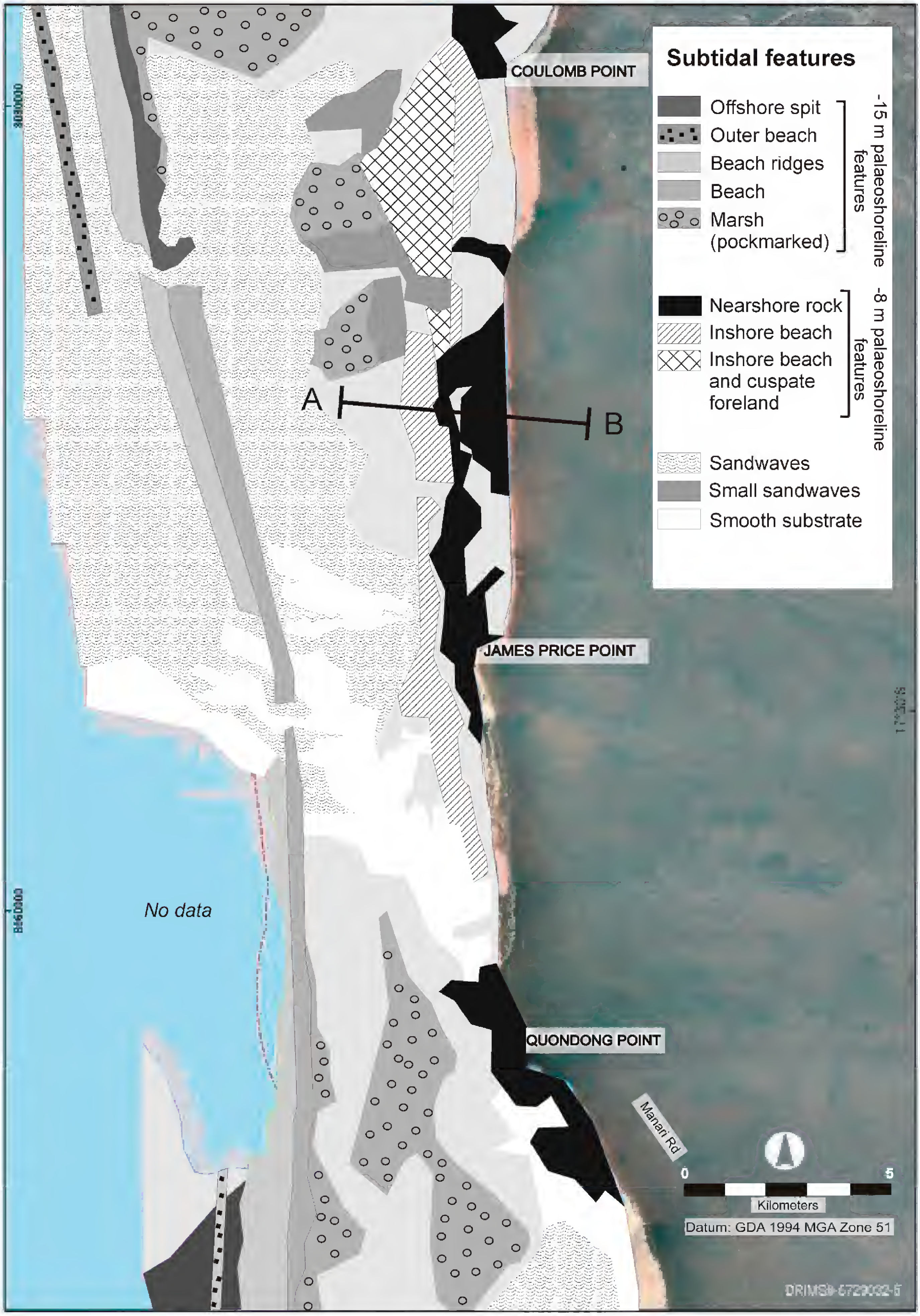


Figure 3. Main interpreted subtidal features in the James Price Point area, based on Figure 2 (sourced from DSD 2010a, Fig. 1–9). Line A–B marks location of section of Figure 4.

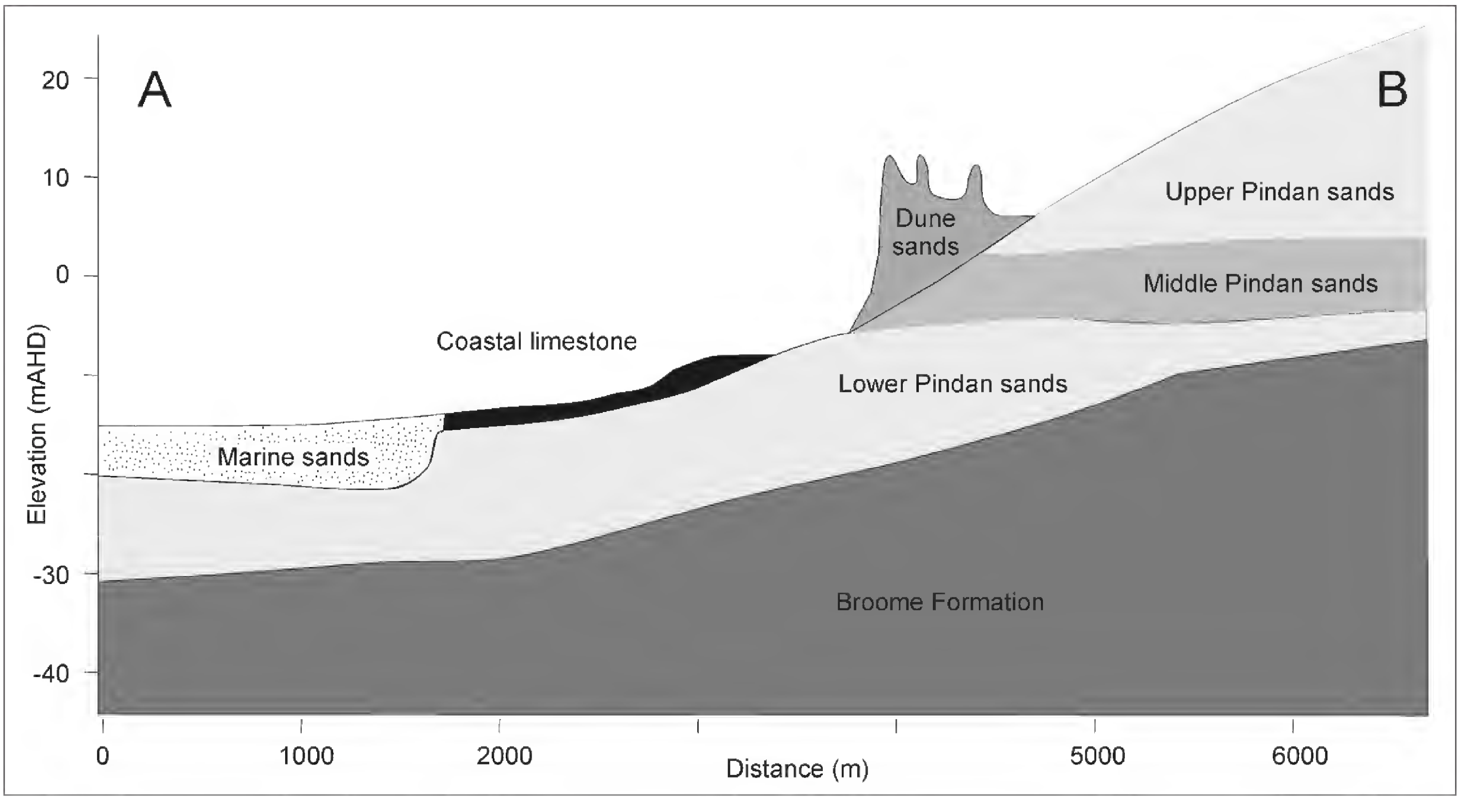


Figure 4. Simplified conceptual vertical cross-section across the coastline developed from the bathymetric survey, four geotechnical boreholes (three to ~20–22 m below seabed, one to 7 m) and some seismic reflection survey results (not to scale; DSD 2010, Fig. 1–6). Coastal limestone is also inferred to occur in places within the lagoon infill but is not illustrated here. Boreholes indicated the Pindan comprised reworked fine and sometimes silty red brown sand. and the basal Broome Formation was represented by weathered very weak sandstone.

with major campsites located within 2 km of the ocean (Smith 1987:43). The vast majority of recorded coastal sites are shell middens, which vary greatly in location, size, density and the types of shell species exploited. The middens tend to occur on both Holocene dunes and low cliffs of ferruginous red sands and soils (Mowanjum Sands), in deflated sedimentary environments and in stratified deposits.

Invariably they include shellfish remains such as mangrove/mudflat species *Terebralia* sp. and *Anadara* sp., and/or rocky intertidal species, such as snail (*Nerita* sp., *Turbo* sp.), murex (*Hexaplex* sp.), *Trochus* sp, clams (*Barbatia* sp.), oyster (*Saccostrea* sp.) and baler shell (*Melo amphora*). The remains of other marine species such as fish, turtle and dugong also occur (Smith 1997; O'Connor & Veth 1993).

A number of well-known silcrete quarries occurs along the west coast of Dampier Peninsula, and many of the shell middens in the south west Kimberley contain stone artefacts (Akerman 1975; Akerman & Bindon 1984). Specialised tools found elsewhere in the Kimberley, such as tula and burren adzes used for wood-working, are largely absent on the Dampier Peninsula (Akerman & Bindon 1984). These are replaced by specialised tools made of shell, including shell adzes, spoons and anvils used to process shellfish, as well as a variety of exotic lithic materials sourced off the peninsula. Further evidence of a flexible coastal-economy is the presence of 39 late-Holocene stonewall fish traps identified along the Dampier coastline (Smith 1997). In the vicinity of Bidyadanga (La Grange) and on the northern Dampier Peninsula, these structures extend for hundreds of metres, and are amongst the largest anthropogenic intertidal structures in Australasia. More fish traps and stone-wall structures may be found by further survey of rocky headlands and intertidal rocky outcrops at low tide (Smith 1997: 20). Clearly, similar structures might exist below the present low tide mark.

Local coastal archaeology

In pre-European Australia, Aboriginal people made extensive use of the James Price Point area, including as a locally important resource area and water source (Smith 1997:46). The area forms a part of an extensive song-cycle, which stretches along the coast from Roebuck Bay to Coulomb Point, 10 km north of James Price Point (Bradshaw & Fry 1989; Roe & Muecke 1983). Notably, the traditions of the local Jabirr Jabirr people – whose lands encompass James Price Point – extend to the adjacent waters and include offshore features that are visible several kilometres away (Leo 2012). The 2015 Department of Aboriginal Affairs (DAA) Register of Aboriginal Sites indicated a number of multi-component archaeological and ethnographic sites, within a 20 km (N-S) x 10 km (E-W) area surrounding the development area. These include mythological and ceremonial sites (12), midden/artefact scatters (21), two quarries, two fish-trap sites and a water source. The two fish traps, *Kardilakan-Jajal* (DAA Site ID 13504) and *Yaljarriny-Gardarlargun* (DAA Site ID 13076, previously *Waldamany*) (Figure 5) constitute the only known prehistoric cultural sites in the intertidal parts of the development area. Three of the Aboriginal shell midden sites, *Yaljarriny-Gardarlargun* (DAA Site

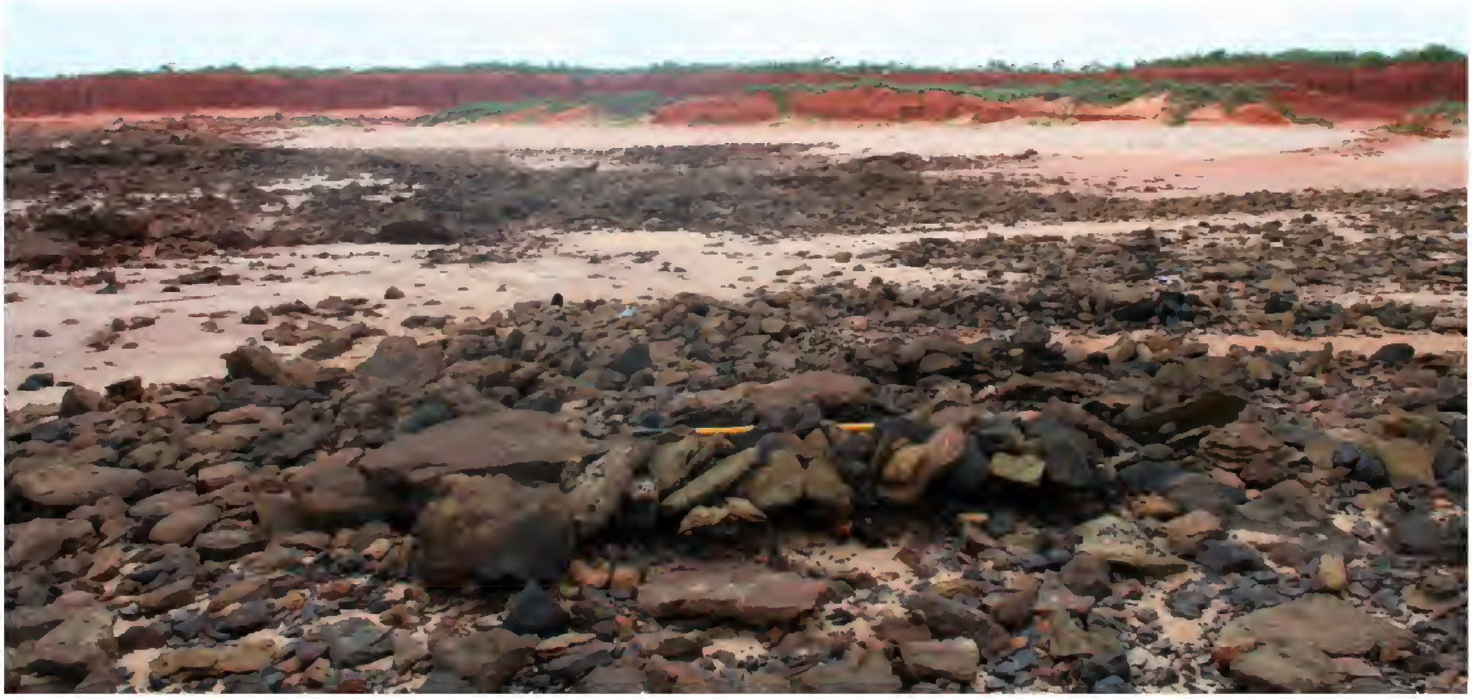


Figure 5. Photo of Yaljarriny-Gardarlargun fish trap exposed at low tide (scale bar is 1 m).

Table 1. List of registered DIA sites (at 2012) and new unregistered sites (Eureka, 2012) at James Price Point. All are terrestrial or coastal. As of 2015, only the Waldaman site remains a registered site.

DIA ID no.	Site name	Site attributes
12864	Inballal Karnbor	Ceremonial, Mythological
12900	Ngarrimarran Junu Quarry	Quarry, Artefacts /scatter
12902	Kundandu	Mythological, Artefacts/scatter, Midden/scatter
12903	Murrjal	Mythological, Artefacts/scatter, Midden/scatter
13076	Waldaman (*Yaljarriny-Gardarlagun*)	Skeletal material/Burial, Fish Trap, Artefacts/ scatter, Midden/scatter
13504	Kardilakan - Jajal	Ceremonial, Mythological, Fish Trap, Artefacts /scatter, Midden/scatter
Not registered	Shell Scatter 1	Midden/scatter
Not registered	Silcrete Quarry Site	Low silcrete outcrop with artefacts
Not registered	Baler Artefact Site (salvaged May 2011)	Broken baler shell artefact and scatter

ID 13076), *Kundandu* (*'Gardarlagun-South'*, DAA Site ID 12902) and *Inballal Karnbor* (DAA Site ID 12864) are located within the coastal dunes of the development area, and other sites within 2 – 3 km of the development area include *Ngarrimarran Junu Quarry* (*'Yaljarriny-Guumbar'*, DAA Site ID 12900) and *Murrjal* (DAA Site ID 12903) (Table 1).

Midden sites range from small, discrete concentrations of stone artefacts and shell material (dinner-time camps), to large multi-component sites extending for kilometres along the coast. Shell middens typically contain a wide range of shellfish species that are found in the adjacent rocky/intertidal environs. Most sites are located in blowouts in the Holocene dunes (Table 3) where accumulations of stone artefacts and shell material, probably representing repeated human visits, are exposed by (episodic) deflation of stratified deposits. The middens' stone artefacts are mostly manufactured from locally available silcrete and are dominated by unmodified flakes, grinding material. Hammerstones, anvils and hearth features are common. Quarry sites are more common on the cliffs that cut into the Mowanjum Sand, with outcrops of high-quality silcrete suitable for tool stone. Lenses of shell and artefacts are also visible in cliff sections but dense grasses and scrub growing on the cliff tops typically obscure surface archaeological material. Surveys also identified an additional shell midden site, a silcrete quarry and a baler-shell artefact

Table 2. Dated AMS measurements for shell material from Waldaman Site (DIA Site ID 13076). Dates, sourced from Eureka 2012, are calibrated at 2 standard deviations (95%) using the Marine Calibration with a regional offset (delta R) of 54 ± 30 based on Squire *et al.* (2013).

Material dated	Lab code	Depth (cm)	Radio-carbon age	Calibrated age (BP)
Muricadae sp.	Wk-31557	4	1385 ± 25 BP	772 - 958
Muricadae sp.	Wk-31558	5	1861 ± 25 BP	1271 - 1463
Saccostrea sp.	Wk-31559	0	1396 ± 26 BP	778 - 971
Saccostrea sp.	Wk-31560	18	1772 ± 27 BP	1180 - 1349
Saccostrea sp.	Wk-31561	100	1876 ± 25 BP	1281 - 1477
Haliotis sp.	Wk-31562	40	1757 ± 28 BP	1173 - 1334
Saccostrea sp.	Wk-31563	100	2486 ± 25 BP	1941 - 2202
Saccostrea sp.	Wk-31564	300	4537 ± 25 BP	4546 - 4803

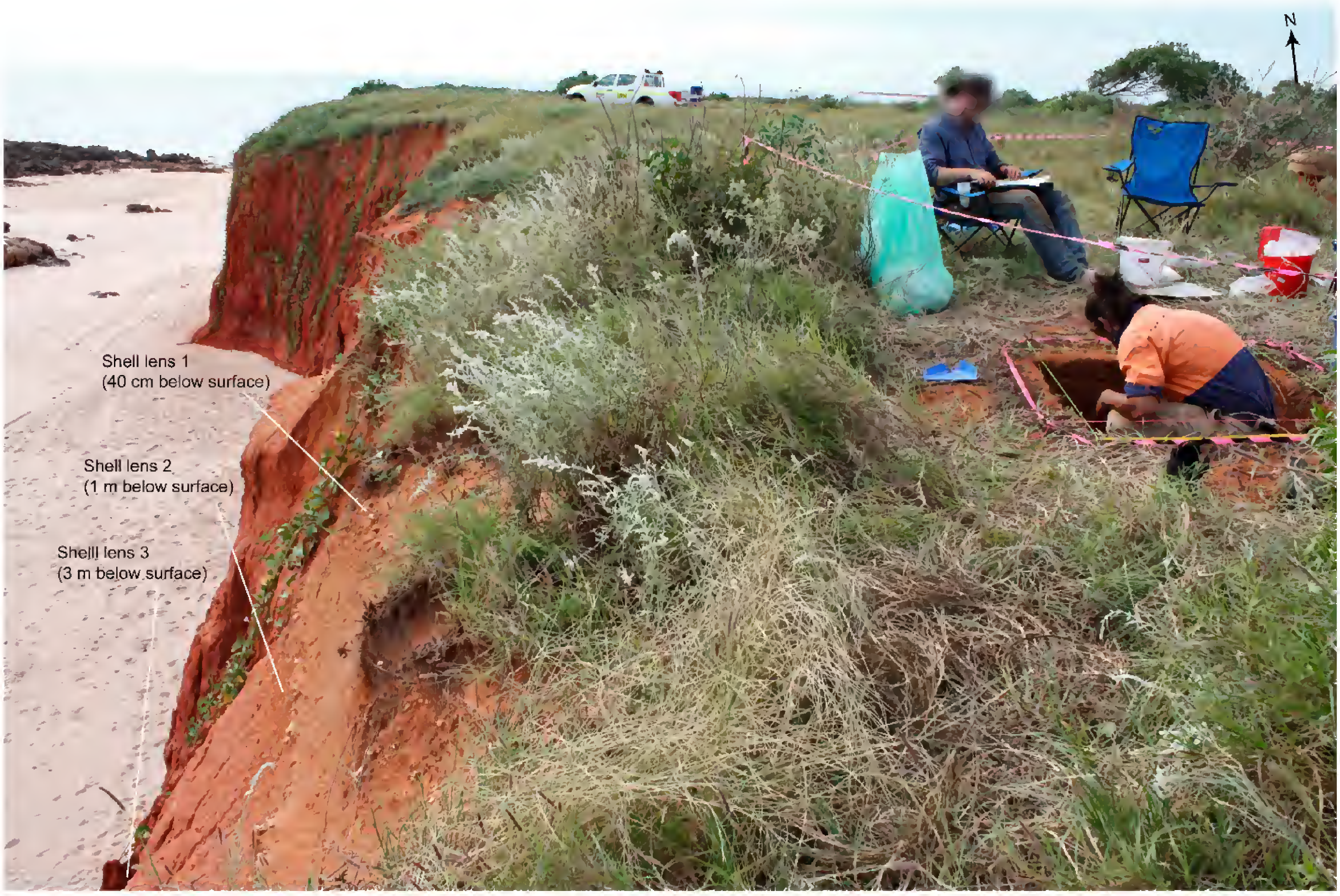


Figure 6. Location of Waldaman excavation at James Price Point. The series of shell lenses in the cliff face date from ~ 5 ky BP,~ 2 ky BP and ~ 1 ky BP respectively up the profile.

site, located 1.6 km, 6 km and 9.6 km respectively inland on the sand sheets (Eureka 2012).

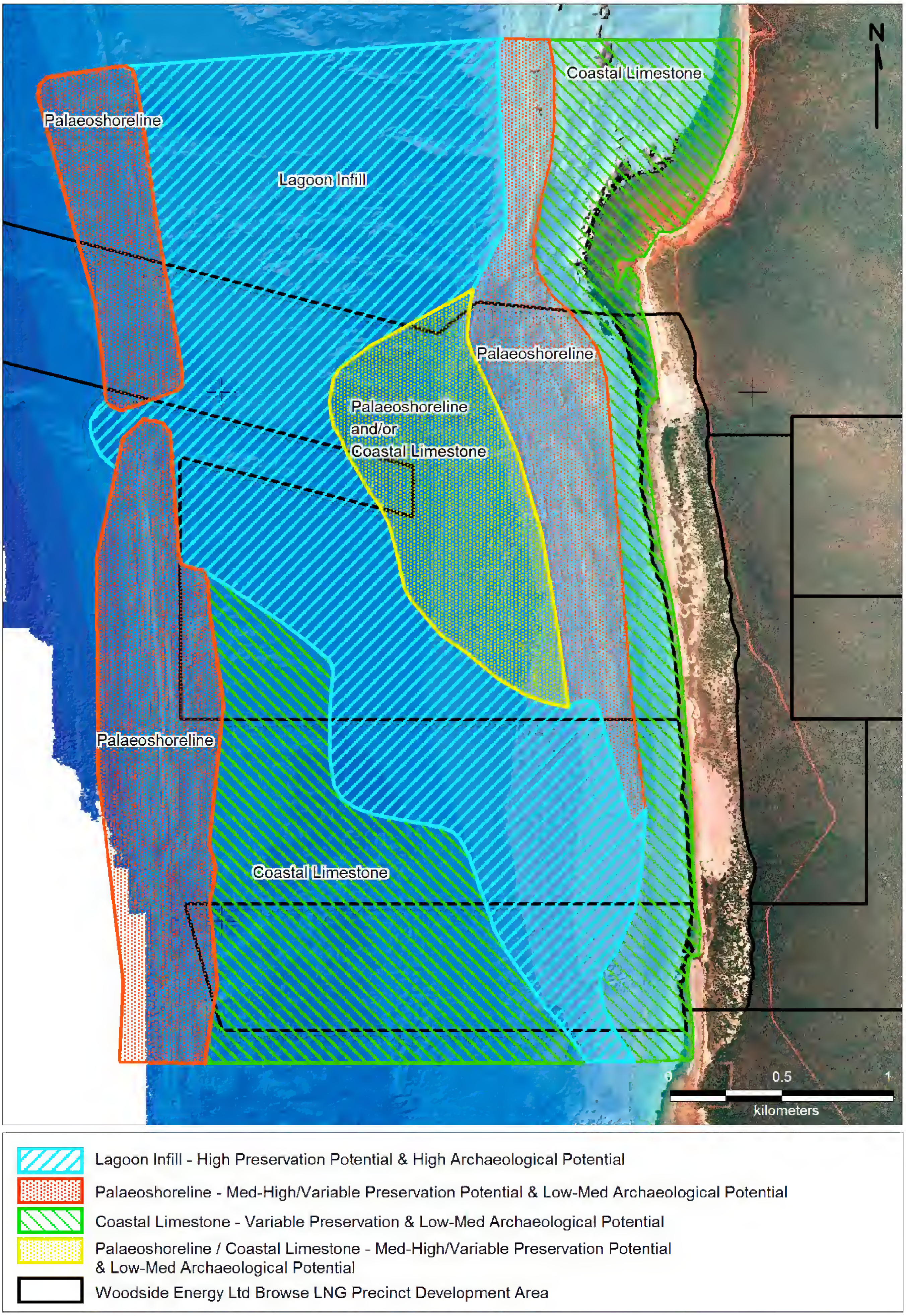
A sample of *Turbo* sp. collected in 1988 from an *in situ* lens of shell at 50–100 cm below the surface of Mowanjum Sands immediately north of James Price Point yielded a radiocarbon age of 989 – 1282 cal. BP (SUA 2826; Smith 1987). A 1 x 1 m excavation, undertaken in 2012 for the Browse project and within the *Yaljarriny-Gardarlagun* site, focused on the cliff edge than 200 m south of this first dated shell lens (Figure 6). Although the basal occupation layer was not reached, an oyster shell (*Saccostrea* sp.) from ~3 m below the surface yielded a radiocarbon age range of 4.8 – 4.5 cal. ky BP (Wk-31564) (Table 2) and indicates use of the site for around the last 5,000 years or more (Eureka 2012). Radiocarbon dating of other shell material, presumably representing food remains, including oyster (*Saccostrea* sp.), abalone (*Haliotis* spp.) and murex (*Muricidae* sp.) from shallower deposits ranged in age from 1.0 – 0.8 ky BP (Wk-31557) to 2.3 –1.9 ky BP (Wk-31563). These dates correspond well with other midden scatters on the south west Kimberley coast (O'Connor & Veth 1993; O'Connor & Sullivan 1994; Smith 1987), and indicate the exploitation of the coastal zone around James Price Point from at least the middle to late Holocene.

DEVELOPMENT OF AN IMAP FOR JAMES PRICE POINT

The following describes the prehistoric marine archaeological potential of the James Price Point area (see also Figure 7; Table 3). In the absence of an absolute chronology for the different landform units in the development area, the assessment of relative age for any associated potential archaeology is based on available geological and stratigraphic information (DSD 2010a, b; Eliot & Eliot 2008; Lessa & Masselink 2006).

Coastal Limestone (archaeological potential = low-medium)

Here we use the term coastal limestone to describe hard cemented features not obviously related to a drowned bathymetric palaeoshoreline feature. Such coastal limestones are sandy coastal sediments of mixed composition but dominated by carbonate grains, which have been cemented by groundwater carbonates, forming beachrock in the case of the intertidal zone. Generally around 1 m thick, tThe coastal limestone's primary location is near the modern shoreline (labelled the 'nearshore rock' of Figure 3), but also occurs in places


N
Palaeoshoreline
Lagoon Infill
Coastal Limestone
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and/or
Coastal Limestone
Palaeoshoreline
Coastal Limestone
0
0.5
1
kilometers
Lagoon Infill - High Preservation Potential & High Archaeological Potential
Palaeoshoreline - Med-High/Variable Preservation Potential & Low-Med Archaeological Potential
Coastal Limestone - Variable Preservation & Low-Med Archaeological Potential
Palaeoshoreline / Coastal Limestone - Med-High/Variable Preservation Potential & Low-Med Archaeological Potential
Woodside Energy Ltd Browse LNG Precinct Development Area

Figure 7. IMAP for shallow marine area offshore from James Price Point, showing areas of relatively low (coastal limestone), medium (palaeoshoreline) and high (lagoon) archaeological potential. Refer text for detail.

Table 3. Inferred archaeological association within terrestrial, coastal and marine depositional environments at James Price Point (JPP).

Landform or sedimentary feature	**Inferred age**	**Sediments**	**Archaeological association**	**Known sites (DAA Site ID) and/or isolated finds**	**Preservation potential**	**Archaeological potential**	**Observed local archaeology and/or related archaeological evidence**
Mowanjum Sand ('Pindan') sand sheets	*Quaternary* Pleistocene	Ferruginous quartz sand with pisoliths, minor clay	Primary	Both (Geotech Scatter **not registered**)	High	Medium	Discrete stone artefacts and stone and shell scatters recorded in Pindan sand sheets, subsurface finds identified through test-pitting
Creeks	*Quaternary* Pleistocene	Mostly ferruginous quartz sand	Secondary	Isolated finds	Low	Medium	Discrete artefacts recorded in ephemeral creeks near Quondong Point (Fig. 1)
Mowanjum Sand ('Pindan') cliffs	*Quaternary* Pleistocene	Ferruginous quartz sand, minor clay	Primary	Both (e.g. ID12427, 12900, 13076)	Low-medium	High	Lenses of shell and artefacts observed in Pindan cliffs at and to the north of JPP.
Aeolian dune system	*Quaternary* Holocene	Carbonate and siliceous shelly sand	Primary, Secondary	Both (e.g. ID13076, 12901, 12902, 12903, 13504)	Medium	High	Numerous middens recorded in deflated and stratified deposits in dunes along many parts of the west Kimberley coast.
Sandy beach	*Quaternary* Holocene	Carbonate and siliceous shelly sand	Secondary	Isolated finds	Low	Low	Isolated artefacts (from cliffs and dune middens) observed on the beach north and south of JPP.
Intertidal flats	*Lower Cretaceous* Broome Sandstone	Cemented sandstone	Primary and Secondary	Sites (e.g. ID 13076, 13504)	Medium	Medium	One registered fish trap at James Price Point, other known and registered fish traps along West Kimberley coast.
Coastal limestone	Pleistocene (Last Interglacial)	Cemented carbonate	Secondary	Isolated finds in beach rock north of JPP	Variable	Low-medium	Cemented artefacts in beach rock (e.g. Cawthra &Uken 2012).
Palaeoshoreline	Early Holocene	Carbonate and siliceous shelly sand	Secondary	Both	Medium-high	Low-medium	Cemented artefacts in fossil dunes (e.g. Dortch &Hesp 1994; Cann *et al* 1991.)
Fossil intertidal flats	Early Holocene	Rock platform	Secondary	Both	Medium-high	High	Known foraging area (e.g. O'Connor & Veth 1993, Smith 1997).
Lagoon infill	Early Holocene	Carbonate and siliceous shelly sand	Primary and Secondary	Isolated finds	High	High	Natural 'sink' for eroded artefacts

as part of the drowned palaeoshorelines and within the lagoon-infill sequence, the latter inferred from areas of relatively strong seismic reflections on the sub-bottom geophysical profiles. Fluctuations in the position of the coastline, and associated changes in the water table, can produce an asynchronous beachrock deposit into which archaeological material might become cemented (e.g. Cawthra & Uken 2012; Dortch & Hesp 1994) sometimes very rapidly (e.g. Friedman 1998). The overall archaeological preservation potential depends very much on cementation and post-drowning marine erosion, and so such beachrock deposits are likely to contain discrete low-density or isolated artefacts.

Palaeoshorelines (archaeological potential = low-medium)

With changes in relative sea level, the location of associated shorelines also changes. Over time, climatic and sedimentological conditions, such as sub-aerial exposure, may allow preservation of palaeoshorelines, including possible combinations of (cemented) beach deposits, beach ridges and coastal dunes. Drowned palaeoshorelines off James Price Point form at least two series of north - south trending linear features with relief of up to 5 m of more above the surrounding seabed, at elevations of - 15 m and - 8 m respectively (Figure 2). Based on relative sea level curves (e.g. Lambeck *et al.* 2014) and ignoring the relatively minor changes in tidal range over the late transgression (see Ward *et al.* 2013), these fossil shorelines may date to ~ 9 ky BP and ~ 6 ky BP respectively. Thus, regardless of any associated archaeology, this series of palaeoshorelines, with excellent seabed expression, is itself of high geological, palaeogeomorphological and sea-level significance.

In parts, the linear palaeoshorelines at JPP and their re-curved ends closely resemble modern barriers, tidal inlets and marshy back-barrier areas (Figure 8). Close to the modern shoreline, particularly north of James Price Point and near Coulomb Point, complex lineations occur which suggest a cuspate shoreline once extended into a semi-protected lagoon or occurred behind a barrier island. Both morphologies are typical of barrier spits that occur where there is an abundant supply of sediment and high rates of longshore transport (Davis & Fitzgerald 2009). As evidenced by archaeological sites on the contemporary coast, these shorelines might have been places dinner-time camps occurred, with consumption of food collected from the adjacent intertidal and lagoon environments. On the landward side of the coastal dune system, preservation of any midden, stone artefact or other archaeological deposits would depend on burial and/or cementation by aeolian processes (e.g. Dortch & Hesp 1994), and on the seaward side by beach accretion and cementation (e.g. Cann *et al.* 1991). The long-term preservation potential of such shoreline deposits (taken as a whole) is medium-high, with a low-medium archaeological potential, mostly of material in a secondary depositional context, i.e. redeposited.

Fossil intertidal flats (archaeological potential = high)

Just north of Coulomb Point and immediately landward of the -15 m palaeoshoreline occur low-gradient relatively smooth platforms (Figure 2). These platforms probably represent a range of intertidal and back-barrier deposits, including reef flats, infilled tidal creeks, salt-marshes and/or salt-flats. Such resource-rich environments were once (e.g. O'Connor & Veth 1993; Smith 1997) and continue to be exploited by humans for a range of traditional marine activities (Bradley 2010). This is an area where fish-trap or stone weirs and midden deposits may be found, as they are now in the contemporary intertidal and adjacent coast around James Price Point. Such back-barrier intertidal deposits typically represent relatively

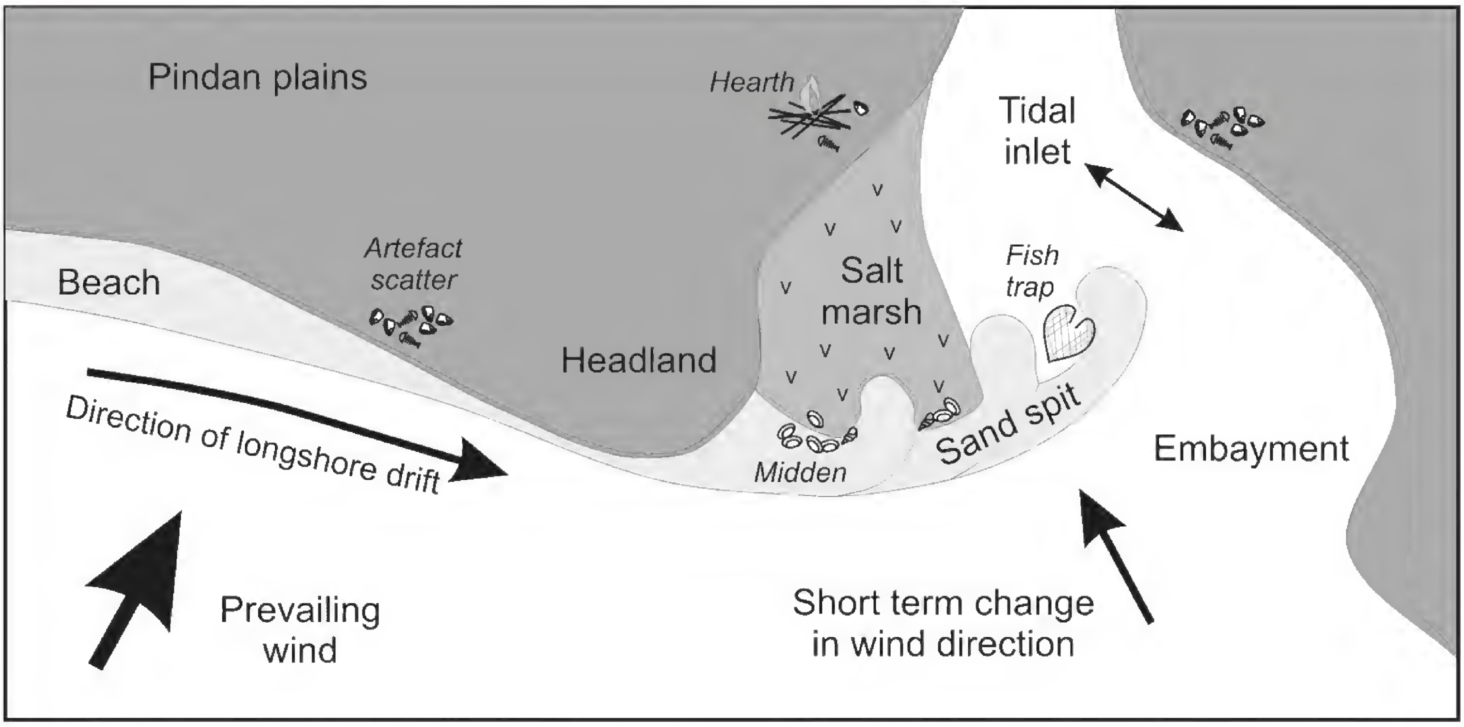

Figure 8. Schematic diagram showing the typical development of a recurved spit, behind which exists a salt marsh, which would have provided a focal area for procurement of intertidal and marine resources by past occupants.

low-energy environments and have probably been largely undisturbed since their accumulation. Overall, these deposits have both high archaeological potential and medium-high preservation potential.

Lagoon infill (archaeological potential = high)

Between the -15 m and -8 m palaeoshorelines is a broad area of bathymetrically relatively smooth sea bed, with surface sediments of clean biogenic sands, rich in foraminifers and, in places, formed into large sand waves (Figure 2). Below much of this area lies between 0.25 m and > 7 m of loose grey to light grey sands, quite uniform in nature throughout the area, and probably of late Holocene age (Figure 4). These sands represent the infill of a fossil lagoon, which is a key unit in the inner-shelf sedimentary succession because it may have changed successively through time during the late parts of the transgression (the last 7,000 years or so) from a brackish or estuarine setting, to a fully marine setting, which changes will have offered a wide range of exploitable resources to past occupants.

There have been relatively few processes through time which will have exported material in bulk from this basin, so these sediments have a high preservation potential for secondary artefacts transported by past and present runoff into the basin from the Pindan sand plain into the zone to landward of the -15 m paleoshoreline feature. Even today it is possible to see artefacts and shell being eroded from the red dunes and transported to the adjacent coast (Figure 9; see also Smith 1997:46). Undisturbed archaeological material may also exist in these complex lagoonal deposits, particularly if there are any discrete patches of organic-rich sediments in the sequence, because these would represent low energy deposits, are least likely to be disturbed and may preserve organic artefacts relatively well.

DISCUSSION

Preservation and significance of relict landscapes

Awareness of submerged pre-European cultural potential in Australia is slowly increasing (Staniforth 2007; Ward *et al.* 2013; 2014b; 2015; Nutley 2014; Veth *et al.* 2014; see also Gusick & Faught 2011), and is being aided by high-quality marine data that makes drowned preserved relict landscape features very apparent. Over the past decade, palaeoshorelines have been mapped and identified across a limited range of shelf settings, including the outer Gulf of Mexico (Allee *et al.* 2012), Bermuda (Iliffe *et al.* 2011) and the Mediterranean (Passaro *et al.* 2011). The interpretations made using the high-resolution bathymetry at James Price Point clearly highlight the presence of relict coastal landscapes here, in common with their broader occurrence on the northwestern continental shelf of Australia (see also Picard *et al.* 2014). At a broad scale, a complex network of valleys, banks, and terraces indicates a drowned terrestrial and coastal landscape that allows for analogies to be made with known archaeological sites on the contemporary coast. Morphologically, the drowned valley systems strongly resemble the modern estuarine complexes present along

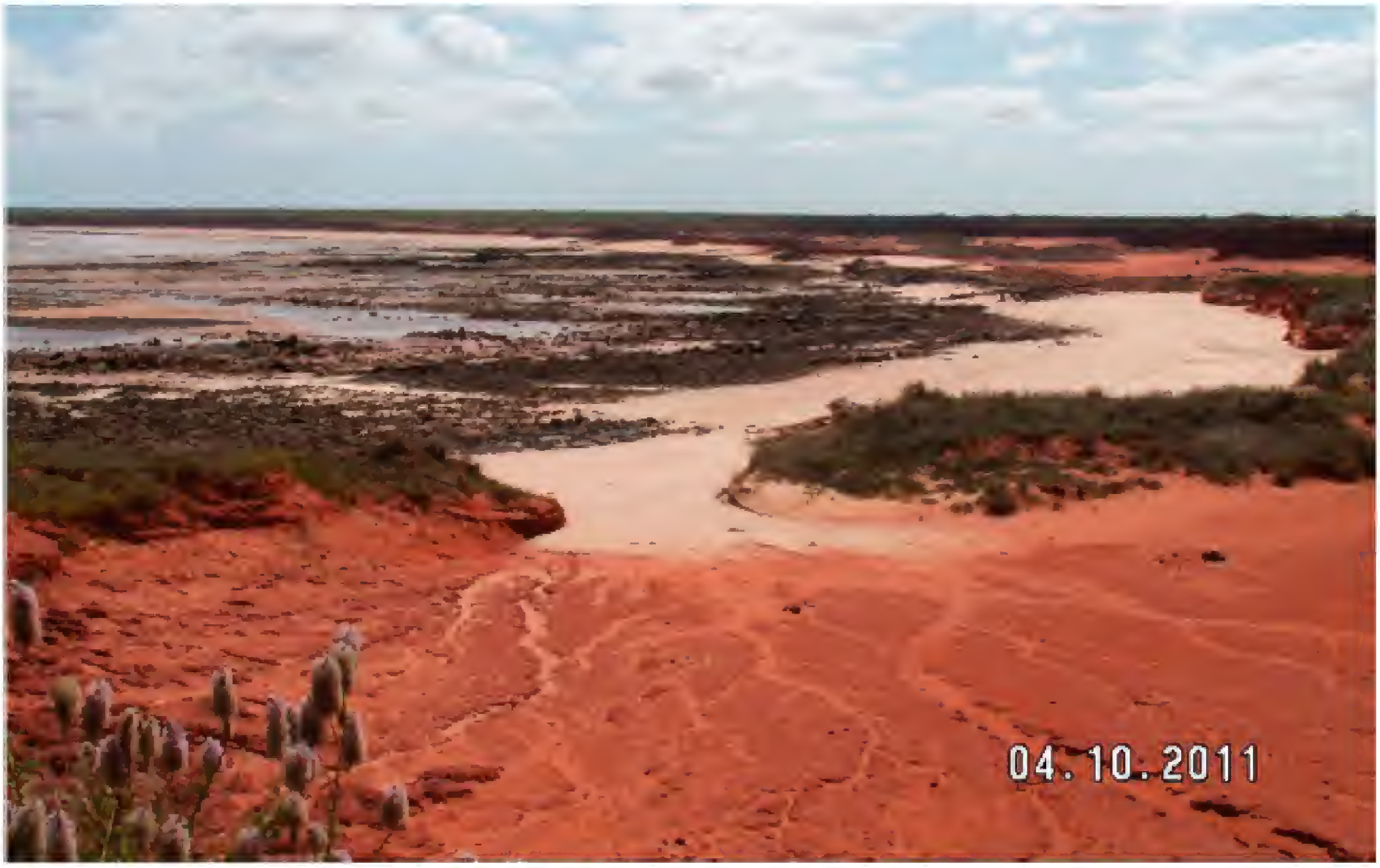

Figure 9. Photo showing erosion and runoff of material from the Mowanjum Sands into the intertidal zone at James Price Point. Artefacts, possibly derived from within the Mowanjum Sands, were observed on these eroding surfaces.

the modern Kimberley coastline and, further, some of the submarine bathymetric ridges are morphologically similar to the beach-ridge coastal plains of northeastern Australia (Semeniuk 2011; Short 2011). The stable tectonic setting means that these submerged features remain at depths that closely match the global sea-level record (Brooke *et al.* 2010; 2014; Nichol & Brooke 2011). Therefore, the area not only provides a unique record of past sea-level change but also potentially of early human coastal resource use in this northern corridor of Australia (see Veth *et al.* 2014; Ward *et al.* 2013; 2014b; 2015).

The wide range of submerged sedimentary deposits in the James Price Point region, each with relatively unambiguous interpretation, represents a suite of environments with the clear potential to contain archaeological sites and artefacts, including those pertaining to early coastal occupation. Specifically, the available submarine geological and bathymetric data clearly indicate that a series of cemented palaeoshoreline deposits are preserved on the seabed, potentially dating (based on sea-level curves) between 9 ky and 6 ky BP (Figure 2), which may also contain lithic or midden deposits. Behind these are intertidal deposits and an infilled lagoon, which are likely to have provided a rich resource for past occupants when this area was exposed and may now preserve archaeological material in either primary or secondary depositional contexts.

The clear bathymetric expression of the fossil dunes is partly a result of the low Holocene rates of sediment accumulation on the shelf, both regionally (Collins 2011) and more locally, which has prevented their burial beneath younger sediments. However, given the cyclone-prone nature of the region, which can readily mobilise sediments across northern Australia's continental shelves (Carter *et al.* 2009; Larcombe & Carter 2004; Larcombe *et al.* 2014), their cemented nature is the key factor in boosting archaeological potential because it will have greatly increased the preservation and archaeological potential not only of the palaeoshoreline deposits themselves but also of those deposits (both primary and secondary) to landward. Further, the clarity of resolution of these submerged past environments, and their likely archaeological potential means that, theoretically at least, there might be the potential to compare artefacts from equivalent deposits of different ages that might indicate early maritime adaptions.

The geoheritage significance of the Kimberley coast is well-documented (Bronx and Semeniuk 2011), and the fossil shorelines of James Price Point are by no means unique – they merely form part of an extensive series of palaeoshorelines of regional scale (Fairbridge 1964 in Wyrwoll 1979:134; James *et al.* 2004; Semeniuk & Searle 1987). However, they are particularly well preserved along the coastline around James Price Point, probably in part due to the lack of supply and accumulation of terrigenous sediments here throughout the Holocene. This palaeogeography is sufficient to warrant the area to be considered of significant geoheritage value (Bruno *et al.* 2014) and worthy of dedicated marine archaeological investigation. High-resolution LIDAR and 3D geophysical survey imagery is continuing to reveal drowned fossil dune ridges and palaeoshoreline sequences along much of the WA continental shelf, including near Perth (Brooke *et al.* 2010; Semeniuk & Searle 1987; Stul *et al.* 2015), at Ningaloo Reef (Collins *et al.* 2003; Nichol *et al.* 2012; WAMSI 2008) and off Port Hedland (BHP Billiton 2008). The clear implication is that there is the potential for pre-European landscapes and marine archaeological sites to be preserved over many hundreds and possibly thousands of kilometres of the WA continental shelf. Some of these may have an archaeological (and palaeoenvireonmental) potential equal or better than JPP because they exist in a relatively protected setting (e.g. within an archipelago) or have a past or present riverine and floodplain around which past occupants may have focused (e.g. Fortescue River) and will have a similarly rich and early (> 10,000 yr old) archaeological context.

Worldwide expansion of marine developments (e.g. ports, harbours, windfarms) introduces a key challenge to research our understanding of the potential impacts of marine development activities on known and potential prehistoric cultural resources (Evans *et al.* 2009; Flemming 2004; Kamoot 2014; Staniforth 2007; Ward *et al.* 2014a). This requires an effective exploration of the key regional issues, including research to support geoarchaeological assessments of marine sustainability and marine cultural heritage management at the State, Territory and National scales, recognising the differences in the cultural (McNiven 2003), physical (see Ward *et al.* 2015) and legislative (e.g. Butterley 2012; 2013) factors relevant to different parts of the Australian coastline. Our work indicates that there is much to be gained in terms of 'pure' and applied research by examining the preserved drowned shorelines, and that effort might focus on lagoon infill and fossil intertidal flats.

CONCLUSIONS

At James Price Point, northern Western Australia, middens, intertidal fish-traps and archaeological excavation at James Price Point provide evidence of coastal exploitation from at least 5 ky BP. In the adjacent marine environment are well-preserved drowned shoreline sediments, which form at least two series of north - south trending linear features with relief of up to 5 m of more above the surrounding seabed, at elevations of - 15 m and - 8 m respectively, which may date to ~ 9 ky BP and ~ 6 ky BP respectively. Along with lagoon and fossil intertidal landscapes, the well-preserved drowned palaeoshoreline are of significant geoheritage value and also have very high archaeological potential. The excellent preservation of relict shoreline features along this and other parts of the northwest Australian continental shelf and coastline highlights the need for greater formal consideration of the submerged prehistoric cultural heritage in marine and coastal developments that is current lacking in the marine statutory framework.

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Hydrological change at Lake Clifton, Western Australia – Evidence from hydrographic time series and isotopic data

MATT FORBES [1] & RYAN VOGWILL [1]

[1] *Natural Resources Branch, Department of Parks and Wildlife, Kensington, Western Australia.*

First author's current address: School of Environmental Earth System Science, Department of Earth Sciences, Stanford University, California, USA.

ABSTRACT

The existence of the unique thrombolite reef at Lake Clifton, Western Australia, relies on a delicate hydrological balance between freshwater input and evaporation driven salinity. Time series hydrographic, in conjunction with hydro-geochemical and stable isotope data, are applied to understand the lake's hydrological regime for the time period 2008-2010. Comparisons with previous multi-decadal hydrologic data are also made to identify longer-term system changes. Water level and salinity data indicate ongoing rainfall and groundwater inputs to Lake Clifton's water balance, however, decreasing rainfall and increasing salinity are threatening the current hydrological balance of the lake and thus potentially its conservation values. Stable isotope data ($\delta^{18}O$ and $\delta^{2}H$) indicate a well-mixed lake water body dominated by evaporative processes, and a possible change in lake hydrology in recent decades. Aqueous elemental data support this, suggesting a possible alteration in the lake's hydrological balance resulting in an increase of the total dissolved solids from groundwater inflows from the eastern side of the lake. Rising temperatures, reduced rainfall and greater evaporation rates combined with reduced fresh groundwater input are resulting in likely groundwater migration of saline groundwater from the Hayward chain of hypersaline lakes and thus in a redistribution of the greater lakes system salt balance towards Lake Clifton, altering the lakes ecosystem.

KEYWORDS: Stable water isotopes, Altered hydrology, RAMSAR, Thrombolites

INTRODUCTION

Increasing salinity, declining water levels, decreasing rainfall, increasing urban encroachment and greater nutrient inputs are key pressures on the current hydrological and ecological balance of the RAMSAR listed Lake Clifton, southwest Western Australia. These threats to conservation values have been highlighted in numerous studies, which have characterized the environmental dynamics of Lake Clifton, including hydrogeological (e.g. Moore, 1987, Commander, 1988, Deeney, 1989, Barr, 2003, Smith *et al* 2010), geochemical (e.g. Moore and Turner, 1988, Davies and Lane, 1996, Rosen *et al* 1996, Knott *et al* 2003, Luu *et al* 2004, Lane *et al* 2013, Smith *et al* 2010) and biological (e.g. Moore *et al* 1984, Burne and Moore 1987, Moore and Burne 1994, John *et al* 2009) investigations. In the northeast corner of the lake an extensive (6 km^2) thrombolite reef occurs, the largest in the southern hemisphere (Moore *et al* 1987, Luu *et al* 2004). Restricted to sub-tidal, sub-littoral and supra-littoral environments of water bodies (Neil, 1984) thrombolites are defined as discrete organo-sedimentary structures, produced by some combination of sediment trapping, binding and precipitation as a result of metabolic activity of micro-organisms (Moore and Burne, 1994). At Lake Clifton, the development and continued persistence of thrombolites has been attributed to continuous inputs of groundwater from the eastern boundary of the lake, providing suitable habitat for microbial mats to form calcified microbialite structures (e.g. Moore *et al* 1984, Burne and Moore, 1987, Moore, 1987). Alterations to this sensitive ecohydrological system are thought to present an increasing threat to the existence of microbial mats responsible for the thrombolite reef (e.g. Moore, 1991, Knott *et al* 2003, Smith *et al* 2010). However, one of the limitations of many previous hydro-geochemical studies has been the sporadic nature of datasets, effectively only providing snapshots of lake system dynamics through time. As a result, knowledge gaps continue to exist, in particular intra-seasonal hydrological data. In this study, we present time series hydrological and hydro-geochemical data for surface, sub-surface, ground and rainwaters spanning a two-year period (2008–2010). We assess the seasonal hydrological functioning of Lake Clifton and importantly combine our new data with historic geochemical and isotopic data to gain a more recent perspective of hydrology and hydrochemical change to the system in recent decades. Importantly this greater appreciation of hydrological change at Lake Clifton can provide insights into how such systems are being modified as a result of climate change alterations to hydrological systems, and the need for higher resolution monitoring programs to identify these rapid changes.

Study Site

Lake Clifton is located in the southern section of the narrow Swan Coastal Plain, southwestern Western

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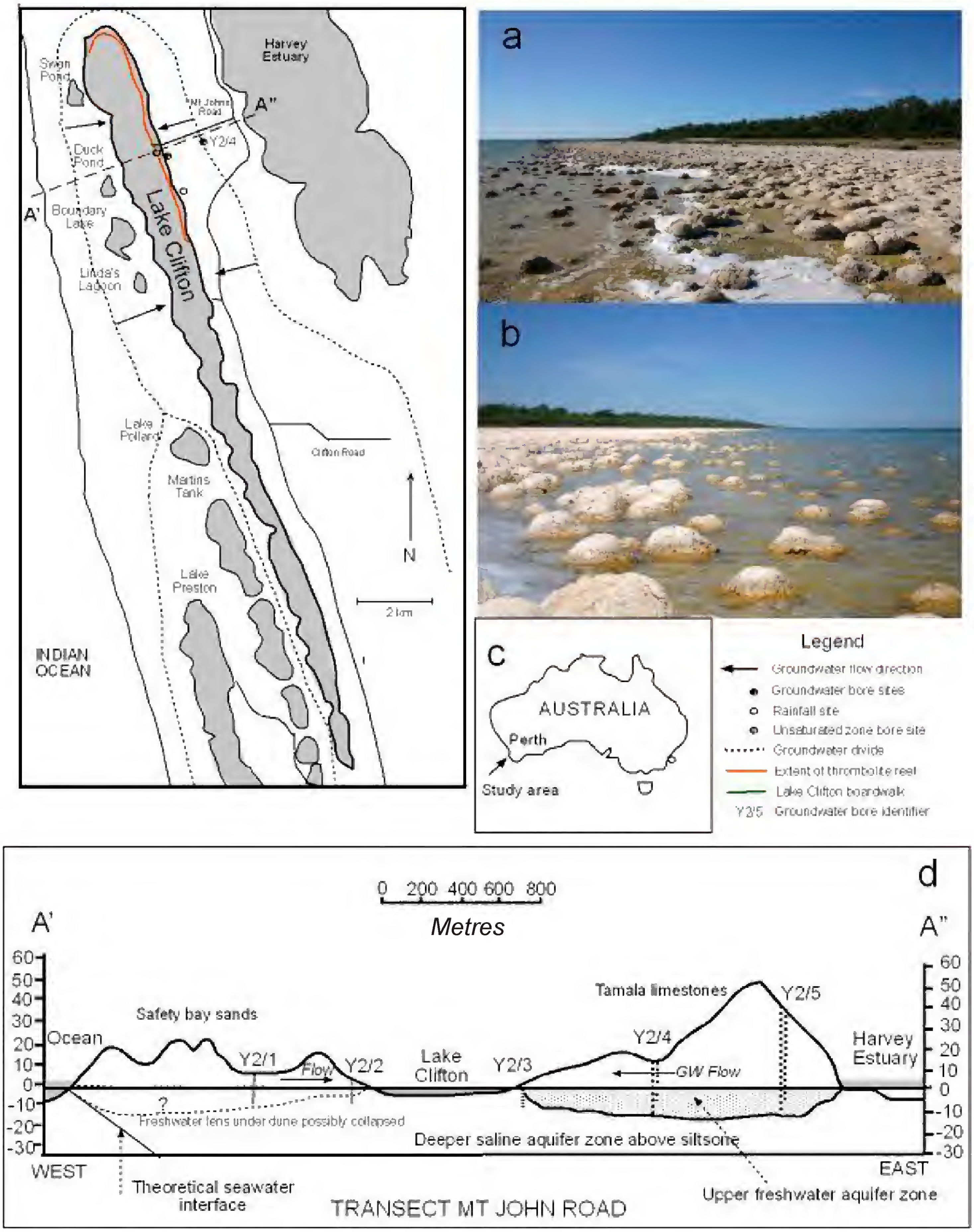

Figure 1. Location map for Lake Clifton within the Yalgorup Lakes System in relation to Perth and greater Western Australia region. Inset a. Thrombolites during summer low water level looking north from Boardwalk. Inset b. Thrombolites during winter high water level looking south from Boardwalk. Inset c. Location of Lake Clifton in southwest Western Australia. Inset d. Hydrogeological cross section of Lake Clifton along Mt Johns Road, including location of Bore network (Modified from Commander 1988). The aquifer system presented in the cross section consists of an upper fresh water lens (referred to in this study as the upper freshwater aquifer) overlying the greater highly saline body.

Australia. It is part of the Yalgorup Lakes system and is bounded by the Precambrian Yilgarn Craton to its east and the Indian Ocean to the west (Figure 1); (Playford *et al* 1976, Commander, 1988, Coshell and Rosen, 1994). The Yalgorup lakes are located in elongated depressions parallel to the coastline, separated by a series of stabilized Pleistocene dune ridges and Holocene dunes. The Pleistocene dune ridges formed between 30 ka to 40 ka BP and Holocene dunes formed during a period of coastal progradation following sea-level changes at 3 to 6 ka BP (Thom and Chappell, 1975, Commander, 1988, Semenuik, 1995). Near surface geology (Figure 1; Inset A), consists predominantly of Quaternary age sands (including calcarenites and minor limestone), underlain by Tamala limestone (Pleistocene), of variable thickness (10 to 100 m) overlying Cretaceous shale and siltstones of the Leederville Formation (Playford, 1971, Commander, 1988, Semenuik, 1995). Sands dominate to the west, while the marine and estuarine fossil containing Tamala Limestone is more prevalent in the central and eastern parts, commonly outcropping near the eastern shoreline of Lake Clifton with the Spearwood Dune System further to the east (McArthur and Bartle, 1980).

The lake is deepest (3 m) in the northern section, and is permanently inundated, whilst the southern third of the lake is ephemeral, drying out over summer (December to February) (Moore *et al* 1987). The thrombolite reef is located on the eastern shoreline in the north of the lake, and is submerged during the winter and spring seasons following increased rainfall (Moore *et al* 1987, Luu *et al* 2004, John *et al* 2009, Smith *et al* 2010). The lake does not experience surface outflows and is thought to receive only occasional minor surface water inputs (Commander, 1988, Davies & Lane, 1996). Hence, Lake Clifton is a groundwater discharge and groundwater through-flow lake that reflects the balance between evaporation, rainfall and groundwater inflow (Moore, 1987, Commander, 1988, Moore, 1993). Previous Total Dissolved Solids (TDS) data indicated that Lake Clifton is predominantly hypersaline, punctuated only by a period of hyposaline conditions in late winter, when rainfall exceeds evaporation (Moore *et al* 1984). Lake TDS has been rising over recent decades (Lane *et al* 2013) with TDS as high as 90 g/L^{-1} recorded in May 2010 (Noble, 2010).

In the Yalgorup lakes system groundwater flow is typically away from the elevated dune ridge areas towards local drainage features such as the coastal lakes and wetlands (e.g. Deeney, 1989). This is apparent for Lake Clifton with groundwater flow from ridges to both the east and west of the lake (Figure 1). A local unconfined groundwater system interacts with the lake (Moore, 1987, Deeney, 1989, Commander, 1988), and is comprised of an upper fresh (2 g.L^{-1}) thin (20 m) zone, overlying a lower dense hypersaline aquifer (>30 g.L^{-1}) to the east. The upper fresh aquifer is directly recharged by rainfall and inflow from the east, while the seawater wedge and downward leakage from saline lakes in the Yalgorup system are the likely origins of the high TDS in the lower aquifer (Moore, 1987, Commander, 1988). The surface water level of Lake Clifton is typically close to or just below sea level. Hydrological boundaries (Figure 1) of Lake Clifton's catchment are the Lake Preston flow system to the south and Martins Tank and Harvey Estuary groundwater divides to the west and east respectively (Commander, 1988).

METHODS

Monitoring Sites

Four sites each representing key components of Lake Clifton's water balance were chosen for high resolution monitoring from 2008 to 2010. The surface water site is located at the northern end of the Lake Clifton boardwalk, where annual water level and salinity monitoring has been ongoing for several decades (Lane *et al* 2013). The upper fresh aquifer was represented by a 15 m deep bore (Department of Water – Bore# Y24A) located approximately 1 km east of the boardwalk. All water levels measured as metres above local datum (deepest point of lake), were then adjusted to Australian Height Datum (AHD) which requires a +4.035 m addition. A further hand augured bore a shallow (1.5 m below ground level) located on the lake's eastern edge approximately 10 m south of the boardwalk was also monitored. The depth of this bore is located in the unsaturated zone, well above the aquifer and fills with sub-surface inflow during the winter and spring seasons. The top of the casing is sufficiently high (1 m) not to be inundated during seasonal peaks in lake water level.

Temperature, pH, Salinity/Electrical Conductivity (EC), and water level data for Lake Clifton surface water were measured at four hour intervals using a multi-sonde logger (*HYDROLAB #MS5*). Levels were measured as a pressure reading by the multi-sonde, which was converted to a level of water, including a correction for lake TDS. Depth of water at the boardwalk was then converted to total lake depth by inference of difference between lake level at boardwalk and that at the deepest part of the lake (e.g. Lane *et al* 2013). Temperature, pH, and TDS/EC measurements were compared to periodic manual measurements preformed with a multi-parameter probe (*OTT QUANTA-G*). Three point (pH) and two point (EC) calibration of the multi-sonde logger and multi-parameter probe were undertaken using 4,7,10 pH buffers and 1000 and 10000 mS/cm calibration standards respectively. For the sub-surface waters and Surficial Aquifer bores, water level, Salinity/EC and temperature were recorded using CTD-DIVER automated data-loggers (*SCHLUMBERGER #DI272*), with salinity/EC calibrated using the same two point EC calibration standards. Water pressure heads (HPa) measured by the CTD-DIVERs were corrected for daily fluctuations in atmospheric barometric pressure measured in bores using a third independent CTD logger placed at the Lake Clifton boardwalk. Periodic manual measurements of bore levels were then applied to correct data to water level in metres above lake floor, and subsequently to Australian Height Datum (AHD). EC measurements have been converted to TDS using the relationships presented in Lane *et al* (2013). Monthly averages and standard deviations of all parameters were derived from approximately individual 180 measurements (six daily). Independent bi-annual manual measurements at Lake Clifton undertaken by Department of Parks and Wildlife, Busselton, Western Australia (Lane *et al* 2013) were used as comparisons to our monthly averages. Local rainfall was measured

Table 1. Average monthly water level, salinity, pH and temperature measurements for Lake Clifton. Period November 2008 to November 2010. Data for months August 2010 onwards are manual readings

	Rainfall mm	**Water Level m AHD**	**Stdev**	**Salinity ppt**	**Stdev**	**pH**	**Stdev**	**Temp Celcius**	**Stdev**
Nov-2008	47.2	8.19	0.1	44.4	0.8	8.5	0.1	20.6	2.2
Dec-2008	5.4	8.11	0.0	47.1	0.7	8.5	0.0	22.0	1.0
Jan-2009	2.8	7.94		64.5		8.4		21.5	
Feb-2009	12.4	7.75	0.0	70.7	0.0	8.3	0.1	21.2	1.1
Mar-2009	5.0	7.57	0.1	70.7	0.0	8.1	0.1	22.2	1.6
Apr-2009	3.4	7.53	0.1	70.7	0.0	8.1	0.0	20.0	1.4
May-2009	54.8	7.54		70.7	0.0	8.2		16.0	
Jun-2009	184.2	7.78	0.1	67.5	1.7	8.4	0.1	13.6	0.8
Jul-2009	129.2	8.09	0.1	60.5	3.2	8.1	0.2	13.7	0.8
Aug-2009	90.6	8.15	0.1	53.9	1.1	7.8	0.0	15.6	1.2
Sep-2009	107.4	8.21	0.1	49.4	0.6	8.6	0.1	16.1	1.0
Oct-2009	12.2	8.21	0.1	50.2	0.9	8.7	0.1	19.1	1.6
Nov-2009	39.4	8.10	0.1	53.8	1.0	8.7	0.1	21.4	2.1
Dec-2009	0	8.02	0.1	59.5	2.9	8.6	0.1	22.9	1.7
Jan-2010	0.2	7.72	0.1	70.1	1.1	8.3	0.1	24.7	1.8
Feb-2010	2.8	7.52	0.0	70.7	0.0	8.1	0.1	24.6	2.1
Mar-2010	68.2	7.48	0.0	70.7	0.0	7.9	0.2	23.5	2.1
Apr-2010	26.4	7.49	0.1	70.7	0.0	7.9	0.1	20.4	1.5
May-2010	75.4	7.58	0.1	74.2*		7.7	0.2	16.9	1.4
Jun-2010	132.8	7.79	0.1	70.7	0.0	7.4	0.0	14.8	1.3
Jul-2010	131	7.85	0.1	67.1	0.3	7.4	0.0	12.9	0.6
Aug-2010	88.8	7.99		59.2		7.8		14.3	
Sep-2010	18.6	7.95		51.8		7.5		15.9	
Oct-2010	15.4	4.04							
Nov-2010	9.2	7.93		62.0		8.1		21.3*	

Salinity measurement for May 2010 was a manual reading of 74.2 ppt. Monthly average of logger data was 70.7 with stdev of 0.0.

Table 2. $\delta^{18}O$ and $\delta^{2}H$ isotope data (per mille) for Lake Clifton 2010.

Sample ID	**Type**[C]	**Location**	**Date**	$\delta^{2}H$	$\delta^{18}O$
YG23	LW	1km south of boardwalk 1m depth	13/05/2010	11.2	1.47
YG21	LW	At Boardwalk depth gauge 1m depth	13/05/2010	16.7	2.89
YG7	LW	1km south of boardwalk 1m depth	10/09/2010	5.4	0.41
YG15	LW	At Boardwalk depth gauge 1m depth	10/09/2010	6.6	0.84
YG30	LW	At boardwalk depth gauge 1m depth	18/11/2010	19.4	3.25
YG33	LW	At boardwalk depth gauge 1m depth	23/11/2010	19.9	3.51
YG31	LW	10m west from Boardwalk logger 1m depth	18/11/2010	19.3	3.40
YG32	LW	15m west from Boardwalk logger 1m depth	18/11/2010	18.1	3.43
YG34	LW	20m west from Boardwalk logger 1m depth	18/11/2010	20.4	3.45
YG35	LW	30m west from Boardwalk logger 1m depth	18/11/2010	18.2	3.27
YG36	LW	40m west from Boardwalk logger 1m depth	18/11/2010	19.1	3.12
YG39	LW	Lake Clifton north west corner 1m depth	23/11/2010	24.0	4.38
YG40	LW	Lake Clifton north east corner 1m depth	23/11/2010	22.0	3.75
YG37	SW	Shoreline 20m north of Boardwalk	23/11/2010	10.5	1.91
YG38	SW	Shoreline 40m south of Boardwalk	23/11/2010	8.9	2.08
YG14 A	SSW[A]	Bore 10m south of Boardwalk	13/05/2010	-6.0	-1.50
YG14 B	SSW[A]	Bore 10m south of Boardwalk	10/09/2010	-5.3	-0.91
YG12	GW	B4 Clifton East	10/09/2010	-19.6	-4.38
YG16	GW	DoW Bore Y24A 1KM East 11m depth	10/09/2010	-15.6	-2.50
YG1	GW	DoW Bore Y32A 1KM East 11m depth	10/09/2010	-17.0	-3.84
YG11	GW	B2 Martins Tank	10/09/2010	-20.8	-4.54
YG28	P	Yalgorup Rainfall	10/06/2010	-13.2	-4.27
	P	Perth Rainfall[B]		-17.4	-3.85

[A] Lake Clifton seep waters are sub-surface waters expressed at surface on lake eastern edge

[B] Perth Rainfall Average isotope values from Turner and Townley 2006

[C] LW- Lake water, SW-surface water, P-Precipitation, GW-Groundwater, SSW-sub-surface water

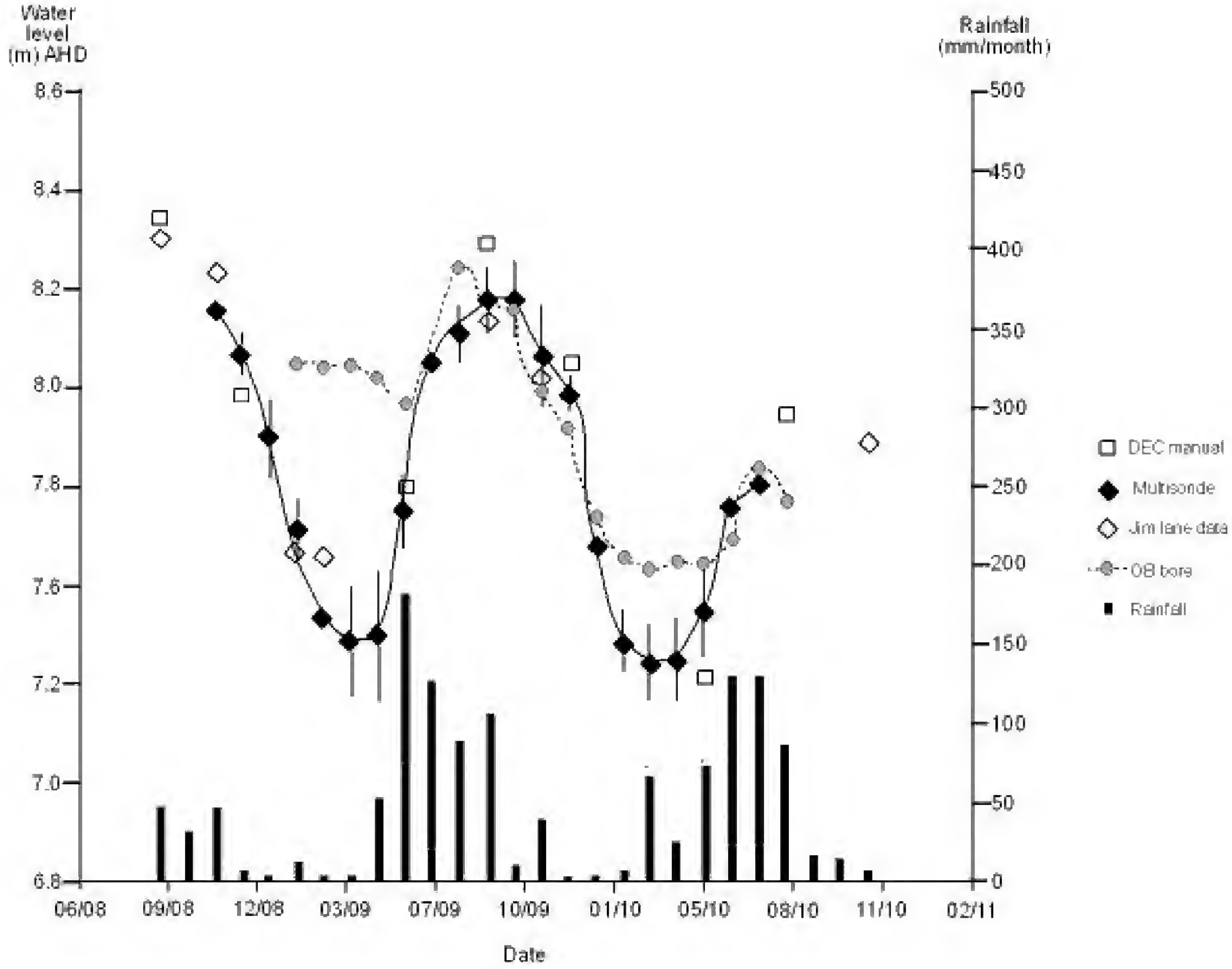

Figure 2. Manual and automated logger measured water levels (metres of depth gauge local datum; +4.035m AHD) for Lake Clifton and the observation bore (1 m BGL), representing unsaturated zone adjacent to the boardwalk for the period November 2008 to November 2010. Also presented are manual lake level measurements (metres) taken for the same period by Lane *et al* 2013. Monthly Rainfall totals representing a composite of measured local rainfall gauge and Mandurah Bureau of Meteorology Station #9977 are also presented.

using a HOBO tipping bucket rain gauge (*ONSET #RG3*) located in an open field on the lakes eastern edge one km south of the boardwalk. Rainfall volumes were logged as 9 am daily totals (24 hr) and validated against data collected at the Bureau of Meteorology Mandurah station (BoM # 9977).

Sample collection

Surface waters were collected manually from specific locations by wading out with bottle or using long pole sampler. Bores were purged (3x volume) and sampled. A single rainfall sample was collected the morning after a 60 mm+ rainfall event on 22nd May 2010 from rain gauge. Water samples for major ion analysis were filtered to <0.45 um, filed in HDPE bottles to overflowing and stored at <4 °C until analysis. Separate 50 ml samples were also collected sealed in small brown glass bottles and stored in darkness at <4 °C for $\delta^{18}O$ and δ^2H analysis.

Stable Isotope Analysis

Stable water isotopes $\delta^{18}O$ and δ^2H were analysed at the Natural Isotopes Laboratory (Perth, Western Australia) with a DLT-100 Liquid-Water Isotope Analyser (Los Gatos Research Inc., Mountain View, CA, USA). Each sample was analysed six times, with the first two being discarded and the last four averaged. Working standard waters, calibrated against IAEA reference waters Vienna Standard Mean Ocean Water-2 (VSMOW), Greenland Ice Sheet Precipitation (GISP) and Standard Light Antarctic Precipitation-2 (SLAP2), were interspaced with the samples for calibration. Data were normalised following Coplen (1988) and expressed as $\delta^{18}O$ and δ^2H per mille (‰) relative to VSMOW. Analytical precision is 0.04 ‰ for $\delta^{18}O$ and 0.3 ‰ for δ^2H (Table 2).

Anions and Cations Analysis

Major Ion analysis (Mg, Ca, Na, K, Cl, Br, F, SO_4^{2-}) of water samples was undertaken at the Perth Water Chemistry Centre, East Perth. Analytical accuracy was checked with an electrical balance to identify the electrical neutrality, with a <5 % deviation between anions and cations considered to be acceptable (Appelo and Postma, 1993).

RESULTS

Lake Clifton Surface Water

Seasonal water level fluctuations of approximately 1 m were observed in Lake Clifton between November 2008 and November 2010 (Figure 2). Minimum lake levels (7.2 m AHD) are observed between May and June, while the highest are in September–November (8.2 m AHD). Measured levels of TDS are significantly greater than seawater (35 $g.L^{-1}$) for the entire monitoring period and fluctuate between 40 and 70 $g.L^{-1}$ seasonally, in an inverse fashion to water level (i.e. TDS lowest in September–November). However, for several months each summer during the observation period salinity reaches the maximum threshold of detection (70 $g.L^{-1}$) for the Hydrolab multi-sonde. The highest manual TDS measurement, (74 $g.L^{-1}$) was recorded in May 2010, using the Quanta-G multi-probe. Furthermore, TDS appears to stay above the 70 $g.L^{-1}$ maximum measurement for the Hydrolab for more months in 2010 than it does in 2009. Lake water temperature varies between 10 °C and 30 °C seasonally with the highest evident in late summer (February–March) and the lowest during the late winter (August–September). Slightly alkaline (8.5) to neutral (7) pHs are observed for the lake water, with most basic (8.5 – 9) values observed in November coinciding with the periods of highest water level. Conversely a more neutral pH (7 – 7.5) is observed during the start of winter when lake levels are at their lowest.

Groundwater

Significant differences in the unsaturated zone waters and upper fresh aquifer were observed between November 2008 and August 2010. The upper fresh aquifer exhibits relatively consistent levels (11.4 to 11.6 m below AHD) is fresh (1 to 2 $g.L^{-1}$) and mildly alkaline pH (8 to 8.5). In comparison the unsaturated zone water levels and salinity are much more variable. Water levels between 7.7 and 8.3 m AHD (highest in the late winter 2009) and remain at or slightly above the base of the lake. Seasonal change for 2010 and 2009 is of a similar magnitude, although lower levels were observed in 2010 (7.7 to 7.9 m AHD) compared to 2009 (8.1 to 8.3m AHD). The TDS of the unsaturated zone waters ranged between 12 to 26 $g.L^{-1}$ (greatest in the summer months of 2010), significantly higher than upper fresh aquifer, yet much lower than the lake water. The unsaturated zone waters are likely representative of rainfall runoff infiltrating into the lake.

Rainfall

Rainfall totals derived from our data and correlated with the Bureau of Meteorology Mandurah station (BoM # 9977) indicate that in 2010 Lake Clifton experienced less precipitation (530 mm) than in 2009 (640 mm). The mean rainfall at the Mandurah station is 671 mm, with the 2010 total being one of the lowest rainfall totals recorded. As expected, rainfall intensity and hence totals were observed to be most significant during the winter months (May to September), with several months experiencing total rainfall exceeding 100 mm. In contrast some months, most notably December through February received rainfall totals less than 10 mm. Several large (>30 mm) individual rain events were identified during the monitoring period, one in particular occurred in March 2010 toward the end of the summer dry season, where 60 mm was recorded in a 24 hr period. Of particular note is that no significant rainfall (>10 mm in 24 hrs) was recorded for three months prior to this event and no rainfall two weeks after. Evaporation data discussed in this study was taken from the same Mandurah BoM station (#9977) used to correlate our measure rainfall totals.

Ionic Chemistry

Ionic chemistry of potential source waters to Lake Clifton were investigated. Na^+ and Cl^- dominate the ionic composition of both lake waters and the upper fresh water Aquifer groundwater. Cation dominance is in the order Na>Mg>Ca>K for the lake water and anion dominance is $Cl>SO_4>HCO_3$. Both cationic and anionic orders of the lake waters are maintained through the year, despite the previously outlined seasonal TDS shifts of 30 $g.L^{-1}$ between Autumn (May 70 g.L-1) and Spring (September 40 $g.L^{-1}$). Both the unsaturated zone waters and the upper fresh water aquifer groundwater display cationic order of abundance as Na>Ca>Mg>K and an anionic order as $Cl>HCO_3>SO_4$ This is despite the unsaturated zone waters having much higher TDS (12 to 26 $g.L^{-1}$), than the upper fresh water aquifer. Rainfall ionic chemistry (Na>Mg>Ca>K and Cl>SO4>HCO3 - TDS <1 $g.L^{-1}$) and seawater ionic chemistry (Na>Mg>Ca>K and $Cl>SO_4>HCO_3$ -TDS 35 $g.L^{-1}$) measured in this study are similar in ionic composition to that stated by Hingston and Gailitis (1976) for the south-west coastal zone of Western Australia.

Isotope Hydrochemistry

Stable deuterium (δ^2H) and oxygen ($\delta^{18}O$) isotope results display distinct variation between the upper fresh water aquifer, unsaturated zone waters, lake water and rainfall (Table 2). Superficial Aquifer δ^2H and $\delta^{18}O$ values range between –15 and –20 ‰ and –2.5 and –4.5 ‰ respectively. A single isotopic measurement for rainfall δ^2H (–13.2 ‰) and $\delta^{18}O$ (–4.3 ‰) was obtained and can be considered similar to that of the upper fresh aquifer. Isotope values for the unsaturated zone waters, δ^2H (–5.3 ‰) and $\delta^{18}O$ (–0.9 ‰), are more enriched than that seen for rainfall and the upper fresh water aquifer. The most enriched isotopic signature was evident for the Lake Clifton surface water, ranging between 6 to 24 ‰ for δ^2H, and 0 and 5 ‰ for $\delta^{18}O$. Furthermore, seasonal variation was apparent in the isotopic composition of the lake water. June exhibited the least enriched values (δ^2H ~6 ‰, $\delta^{18}O$~0 ‰), while November displayed the most enriched δ^2H (20 ‰) and $\delta^{18}O$ (3 ‰) values.

DISCUSSION

Time series hydrological data presented in this study in conjunction with seasonal geochemical and isotopic analysis, provide insight into the hydrological functioning of the Lake Clifton System for the period 2008 to 2010. Previously seasonal shifts in hydrology were primarily interpreted from the 25 yr long term lake level and salinity monitoring program (Lane *et al* 2013), which consisted of twice-yearly September and

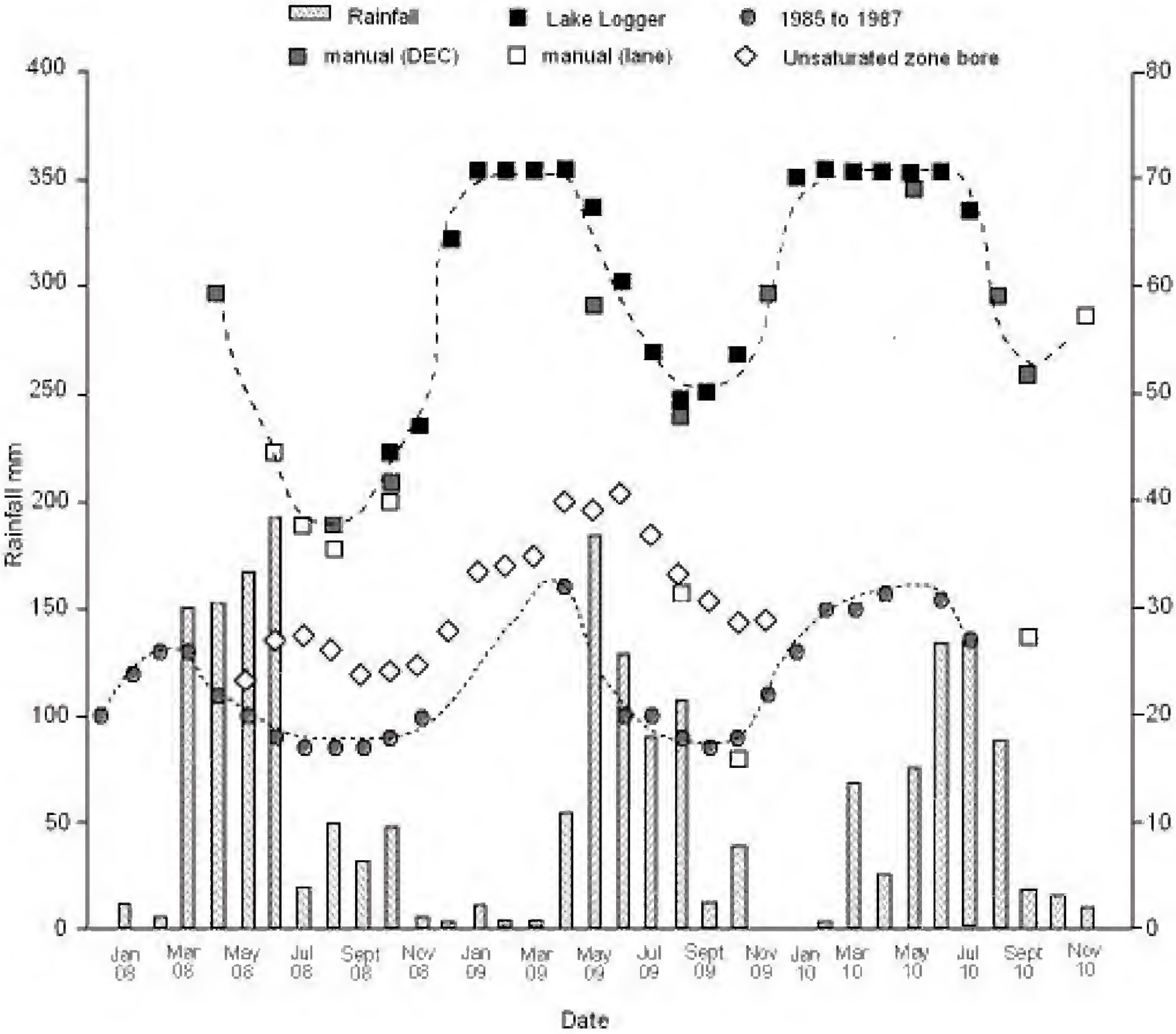

Figure 3. Manual and automated logger measured salinity concentrations (g.L^{-1}) for Lake Clifton and sub surface waters (meters of depth gauge local datum; +4.035 m AHD) bore for the November 2008 to November 2010 monitoring period. Simultaneous measurement data from Lane (*et al* 2013) also presented.

November measurements, taken when lake and salinity levels were anticipated to be at their respective peaks and troughs. This protocol followed the strategy employed by Moore (1987) who stated that maximum lake water levels occurred approximately four months after the anticipated July rainfall maximum. Our averaged monthly lake data confirm the Moore (1987) strategy with water level maximums and salinity minimums around September, two to three months after peak in rainfall totals. A strong relationship between the change in monthly average lake level and rainfall totals (Figure 4) is identified for the 2008 to 2010 monitoring period ($R^2 = 0.75$; $P < 0.001$). This relationship matches that developed using the 20-plus years of biannual data, used recently by Smith *et al* (2010) that show water levels in Lake Clifton are still highly dependent on rainfall.

Moore (1987) used the identification of this three to four-month delay between peaks in rainfall and lake level as evidence of groundwater inflows into the lake to its importance to water levels in Lake Clifton. To quantify the contribution of groundwater infiltration for 1984, regional annual precipitation (762 mm), measured evaporation (1369 mm) and change in lake level were assessed. Moore (1987), assumed that 80 % of rainfall occurred between March and September and identified precipitation during this period to exceed evaporation by 112 mm. Lake Clifton water level however rose by 864 mm, meaning shallow groundwater inflow contributed significantly to lake level and hence composition in 1984. In order to assess the contributions of groundwater to lake level we repeated the calculations done by Moore (1987) using both our 2009 and 2010 seasonal data. Rainfall was seen to exceed evaporation by just 5 mm in 2009 and was below evaporation by 125 mm in 2010 during the winter rain periods. For both these years' lake levels fluctuated by 680 mm and 530 mm respectively,

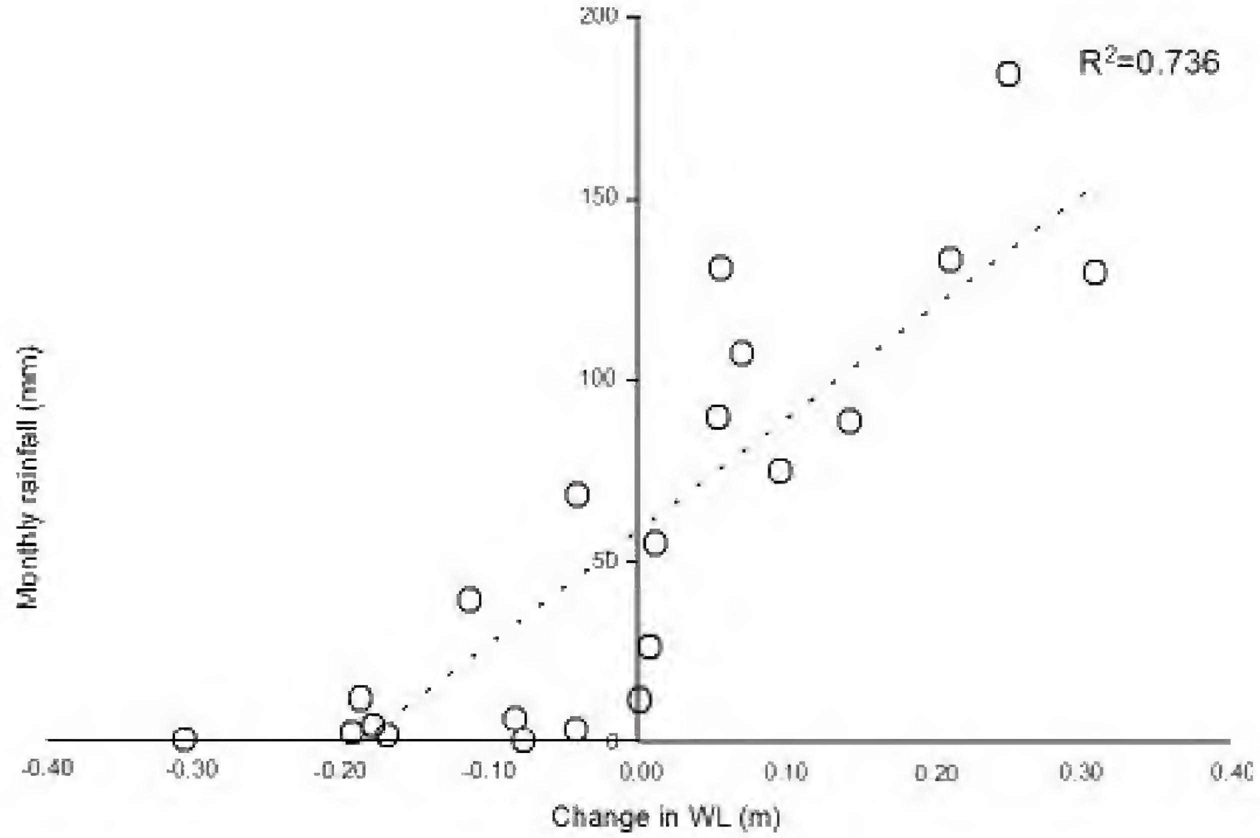

Figure 4. Lake water level and lake edge sub-surface waters response to 60mm rainfall event over one week in March 2010. Note during the same period lake salinity remained at 70 g.L^{-1} the maximum measurement capacity of the Hydrosonde logger.

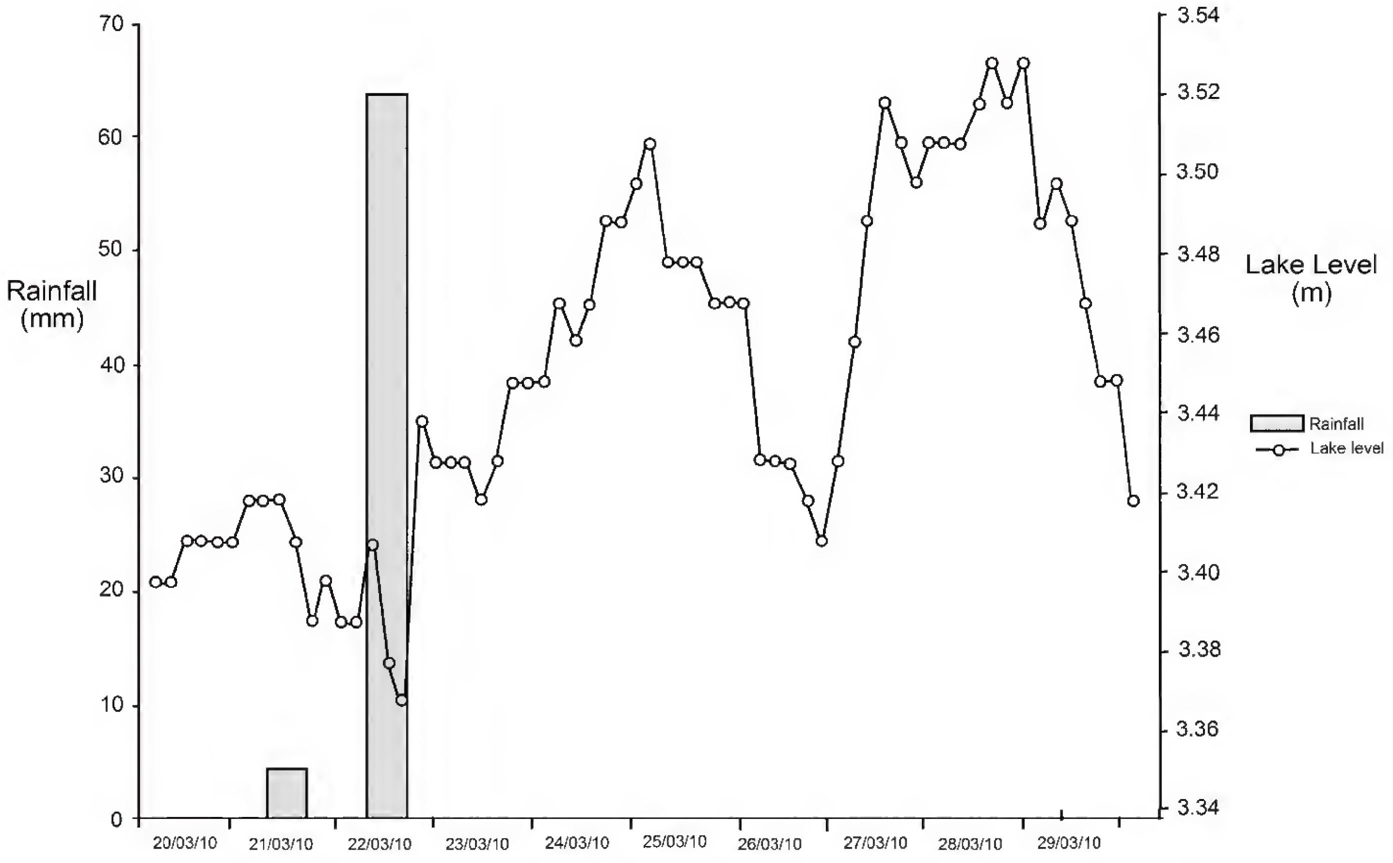

Figure 5. Relationship between monthly change in Lake Clifton water level and accumulated monthly rainfall for the 2008 to 2010 period.

hence according to these parameters groundwater inflow contributed 752 mm in 1984, 675 mm in 2009 and 655 mm in 2010. These data indicate a possible decadal scale reduction in groundwater input to the lake, and that its water balance is highly dependent on winter rainfall totals and winter evaporation deficit.

Further to the Moore (1987) findings, Knott *et al* (2003) also argued for the importance of contributions by groundwater to the Lake Clifton water balance. Looking at the long term (1980 – 2000) salinity, lake level and rainfall data, they identified no relationship between annual spring-time salinity levels, thus implicating groundwater inflow as a key driver of lake salinity. Close inspection of our daily measured lake levels identifies immediate responses to rainfall, which further supports both rainfall and groundwater recharge as important input components to Lake Clifton. In March 2010, at the end of the summer dry season the lake area experienced a significant rainfall event (60 mm in 24 hours). In the following 48 hrs after the rain event lake level rose by 150 mm. A second 100 mm increase in lake level was identified four days after the rainfall event (Figure 5). A brief increase in water in the unsaturated zone proximal to the lakes edge of 100 mm immediately after the rain event was also identified. In comparison there was no notable change in water levels in the upper fresh water aquifer. Hence this two-phase increase in lake levels resulting from this isolated rainfall event is interpreted as comprising an initial phase of direct rainfall recharge, followed by a second phase of infiltration through the unsaturated zone combined with and possible surface runoff. Surface water recharge into Lake Clifton has been noted before by Davies and Lane (1996), but only after rainfall events of in excess of 10 mm in a 48 hr period, and even then it is thought to only contribute minimally to the overall water balance of Lake Clifton. However, reduction in the area of native vegetation buffer zones around the lake over the last two decades, may have allowed for a potential increase in surface water runoff into Lake Clifton. Interestingly lake salinity during the storm period where the sharp increase in water level was observed, remained at 70 g.L^{-1} the maximum reading for the multi-sonde logger. Hence whether this rain event affected salinity in the lake cannot be assessed.

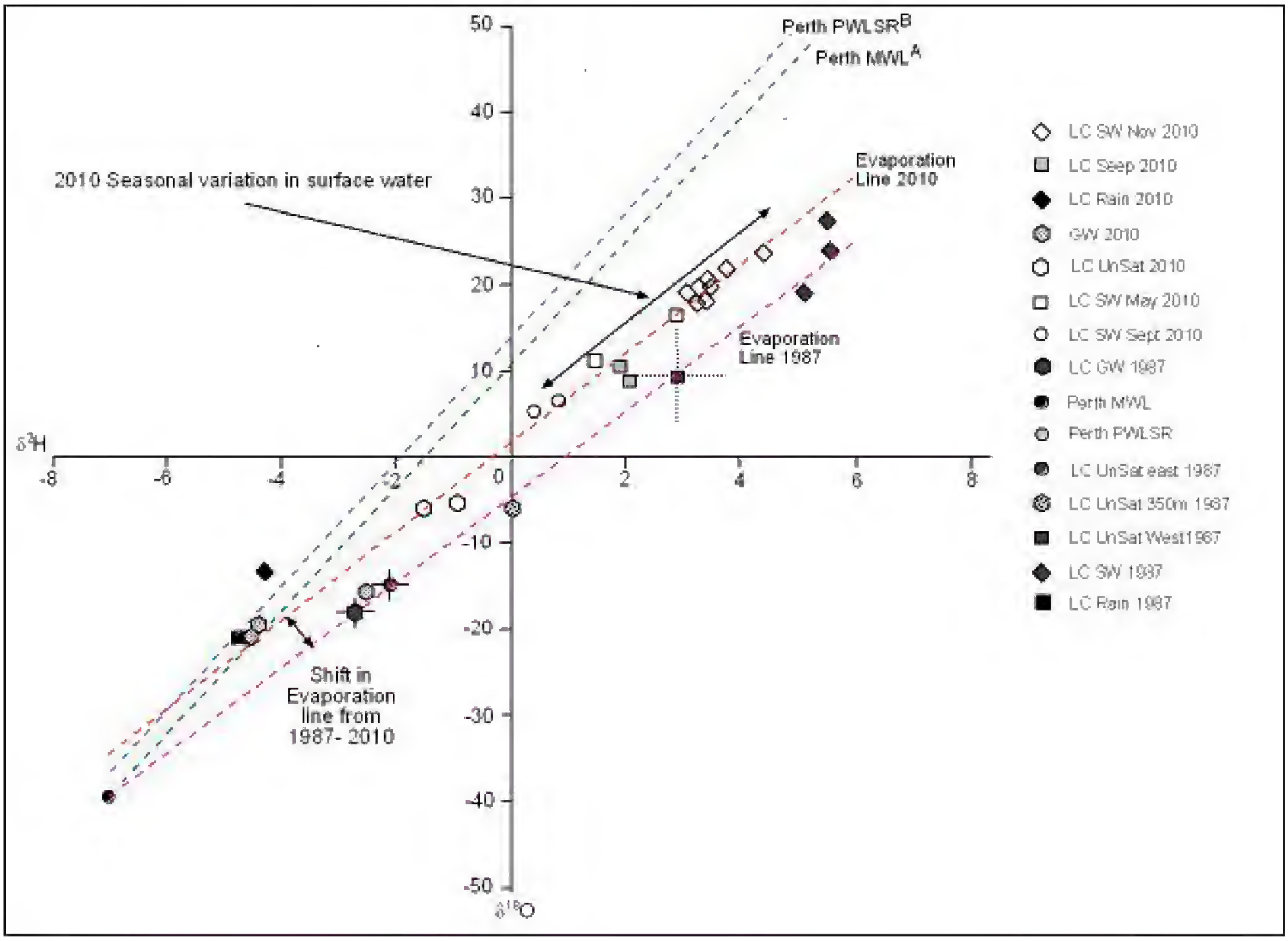

Figure 6. δ^{2}H and δ^{18}O data for Lake Clifton surface water, groundwater (Superficial Aquifer), sub-surface waters (1 m below ground level) and rainfall. Surface water isotopic data represents June, September and November 2010. Also included are δ^{2}H and δ^{18}O data for sub-surface waters from Moore (*et al* 1987) and for seep waters (sub-surface water expression) for November 2010. Evident is a shift in the intersection between the evaporation lines for 1987 and 2010 the local meteoric water lines (LMWL) for Perth (Turner and Townley 2006, Hughes and Crawford 2012).

Variation in Lake Clifton's TDS is seasonal and similar to those identified for lake levels. Lowest yearly recordings of between 35 and 50 g.L^{-1}, are evident in September each year, corresponding to peaks in water level. Highest salinity (>70 g.L^{-1} TDS) concentration was identified in the summer months, when lake levels are at their lowest. However, the exact timing and value of the peak could not be confirmed as many salinity readings exceeded the detection limitations of the multi-sonde instrumentation. A manual measurement of 74 g.L^{-1} for May 2010 was the highest salinity reading recorded during the two-year monitoring period. Between 2008 and 2010, Lane *et al* (2013) also measured lake water TDS at the inner and outer sedge areas, where ground water seepage is thought to enter the lake. Of further interest is that the number of months in 2010 where salinity (EC) exceeded 70 g.L^{-1} was 6 compared to 4 months in 2009, a year that experienced over 100 mm extra rainfall, further implicating rainfall as an important factor in lake water salinity. It would also appear that the salinity minimum observed each spring (Figure 3) increased slightly from 2008 to 2010 following the long-term trend of increasing lake salinity, however seasonal effects would need to be considered to evaluate this potential trend over time in more detail. Our monthly data supported by that from Lane *et al* (2013) confirms the Smith *et al* (2010) hypothesis that annual minimum lake salinity (EC) is 40 to 50 g.L^{-1} and occurs between August through October, implying that Lake Clifton can no longer be considered hyposaline at any stage of the year, like it had been categorised in previously (Moore, 1987, 2003).

In most hydrological systems, evaporation from open water bodies is the principle isotopic fractionation mechanism and the driving of evaporative isotopic enrichment. Variation in δ^{18}O and δ^{2}H in lake waters is strongly influenced by its temperature, salinity and relative humidity (e.g. Kendall and Caldwell, 1998). Lake Clifton's surface water stable isotopic data (δ^{18}O and δ^{2}H) exhibit characteristics expected for a coastal lake system in the south-west of Western Australia, whose water composition is dominated by oceanic characteristics that are subjected to strong evaporation processes (e.g. Sharma and Hughes, 1985, Marimuthu *et al* 2005, Turner and Townley, 2006).

Isotopic data, δ^{2}H –18.25 ‰ (stdev 2.37; n = 4) and δ^{18}O –3.82 ‰ (stdev 0.93; n = 4) for the upper fresh aquifer is similar to regional rainfall (δ^{2}H –17.4 ‰; δ^{18}O –3.85 ‰) and falls on the well-established Local Meteoric Water Line (LMWL) for Perth, Western Australia $\delta^{2}H = 7.15*\delta^{18}O + 10.6$ (e.g. Turner and Townley, 2006, Liu *et al* 2010, Hughes and Crawford, 2012). The evaporation line, the linear equation that represents the evolution of evaporated water (e.g. Allison *et al* 1979), is $\delta^{2}H = 5.18*\delta^{18}O + 1.61$ has a lower slope than the LMWL as evaporation causes deviations from the LMWL (Gibson *et al* 1993). Lake Clifton surface waters are significantly more enriched than the waters of the unsaturated zone, upper fresh groundwater and rainfall, indicating a strong evaporative influence. surface seep waters identified on the eastern edge of Lake Clifton during the winter rain season display more enriched δ^{18}O and δ^{2}H than the upper fresh aquifer groundwater due to its longer period of exposure at the surface and evaporative isotopic enrichment.

δ^{2}H and δ^{18}O isotopic data for Lake Clifton for the three months of June, September and November in conjunction with monthly salinity data confirm the impact of seasonal evaporative on lake chemistry. September (n=2) displays the least enriched δ^{2}H and δ^{18}O values with June (n=2) more enriched and November (n=8) the most enriched. September is also the month where minimum salinity is observed suggesting that this is the month where the lake waters composition is most likely influenced by combined contributions from rainfall and groundwater inflows.

Besides seasonal evaporation processes, δ^{2}H and δ^{18}O data has been used previously (Moore, 1987, 1993 and Moore and Turner, 1988) to identify the presence of groundwater infiltration into eastern Lake Clifton. In that study sub-surface waters sampled across the first 350 m of the eastern side of the lake derived an isotopic signature (δ^{2}H ~ –14.9 ‰ and δ^{18}O ~ –2.11 ‰) similar to regional groundwater, but much less enriched than the lake water itself (δ^{2}H ~ 5 ‰ and δ^{18}O ~ 25 ‰). δ^{2}H and δ^{18}O values for unsaturated zone waters more than 350 m west from the lake's eastern edge were much more enriched with signatures more akin to lake waters. While similar groundwater δ^{2}H and δ^{18}O values are evident for both 1987 and 2010 data, unsaturated zone waters analysed in 1987 are clearly less enriched than those in 2010. Comparisons of evaporations lines for 1987 ($\delta^{2}H = 4.98*\delta^{18}O – 4.55$) for the Moore (1988,1993) data set and for 2010 sees the 1987 evaporation line having greater separation from the LMWL than the 2010 evaporation line. Furthermore, the δ^{2}H and δ^{18}O intersection point of the two evaporation lines with the LMWL are different (1987 ~ –7 ‰ and –40 ‰ and 2010 ~ –4 ‰ and –18 ‰, for δ^{2}H and δ^{18}O respectively). The intersection of the evaporation line with the LMWL is a representation of the average composition of source water entering a lake system (e.g. Gibson *et al* 1993, Walker and Krabbenhoft, 1998, Cartwright *et al* 2004, 2013). Thus we interpret the shift in the evaporation line signature between 1987 and 2010 as evidence of a shift in the water balance of Lake Clifton System due to a changing source of water. This hypothesis requires further validation considering more recent data and also greater number of groundwater samples. This change could manifest from a reduction in total rainfall and groundwater inflow or a change in the composition source of groundwater. A preliminary linear mixing model of surface waters using δ^{18}O and Cl^{-} data following that applied by Price *et al* (2012) implies a dominant source of groundwater for 2010 to the lake at an approximate δ^{18}O value of –4 ‰, which is similar to that identified for the upper fresh aquifer on the eastern side of the lake.

Rosen *et al* (1996) reported 1995 ionic abundance order for lake waters as Na>Mg>Ca>K and $Cl>SO_4>HCO_3$, in proportions similar to seawater. These findings were in accordance with numerous other hydro-chemical studies of the lake (Williams and Buckney, 1976, Moore, 1987, Burke and Knott, 1989). Moore (1987) found that the regional groundwater flowing into Lake Clifton had ionic abundances of Na>Ca>Mg>K and $Cl>HCO_3>SO_4$, that had been consistent over time. Comparisons of our 2010 data to these previous studies identify similar order of abundances for both surface and ground waters. However, significant increases in concentration of all major cations (Ca, K, Na, Mg) and Cl^- (Figures 7a,b,c) are evident for lake waters since the 1970s. Increases in cations and Cl^- in the upper fresh groundwater, albeit of a lesser magnitude than that evident in lake water (Figures 8a,b,c) are also apparent since the 1980s. Comparisons of molar ratios of water bodies shed more light on this increase by suggesting a possible changing hydrochemistry of groundwater. Falling Ca/Cl and Mg/Cl ratios in lake waters and the upper fresh aquifer ground waters of the system between 1984 and 2010 (Figures 7d, 8d) combined with the increasing ionic concentrations suggest a general shift to the ionic chemistry of seawater.

It is well established from previous studies (e.g. Knott *et al* 2003, Smith *et al* 2010) that Lake Clifton has been experiencing increasing salinity over the last few decades, the causes of which have been tackled by several investigations. Barr (2003) used the established data sets derived and water balance for the lake and examined three possible mechanisms for the increasing lake salinity. These were 1) observed reductions in rainfall and reduced freshwater inflow; 2) the dewatering of the Dawesville Channel to the north of Lake Clifton, causing a rise in the level of the underlying saline groundwater; and 3) bore water extraction within the catchment area reducing freshwater input to the lake. Results from modelling these scenarios indicated that the lake system was extremely sensitive to both rainfall and evaporation rates. Thus Barr (2003) concluded that the reduction in water levels and increasing salinity were most likely a result of changing climatic conditions.

Further to the work done by Barr (2003), Knott *et al* (2003) compared lake salt mass and rainfall to determine whether rainfall was a key driving factor in determining lake salinity. Knott *et al* (2003) investigated data from

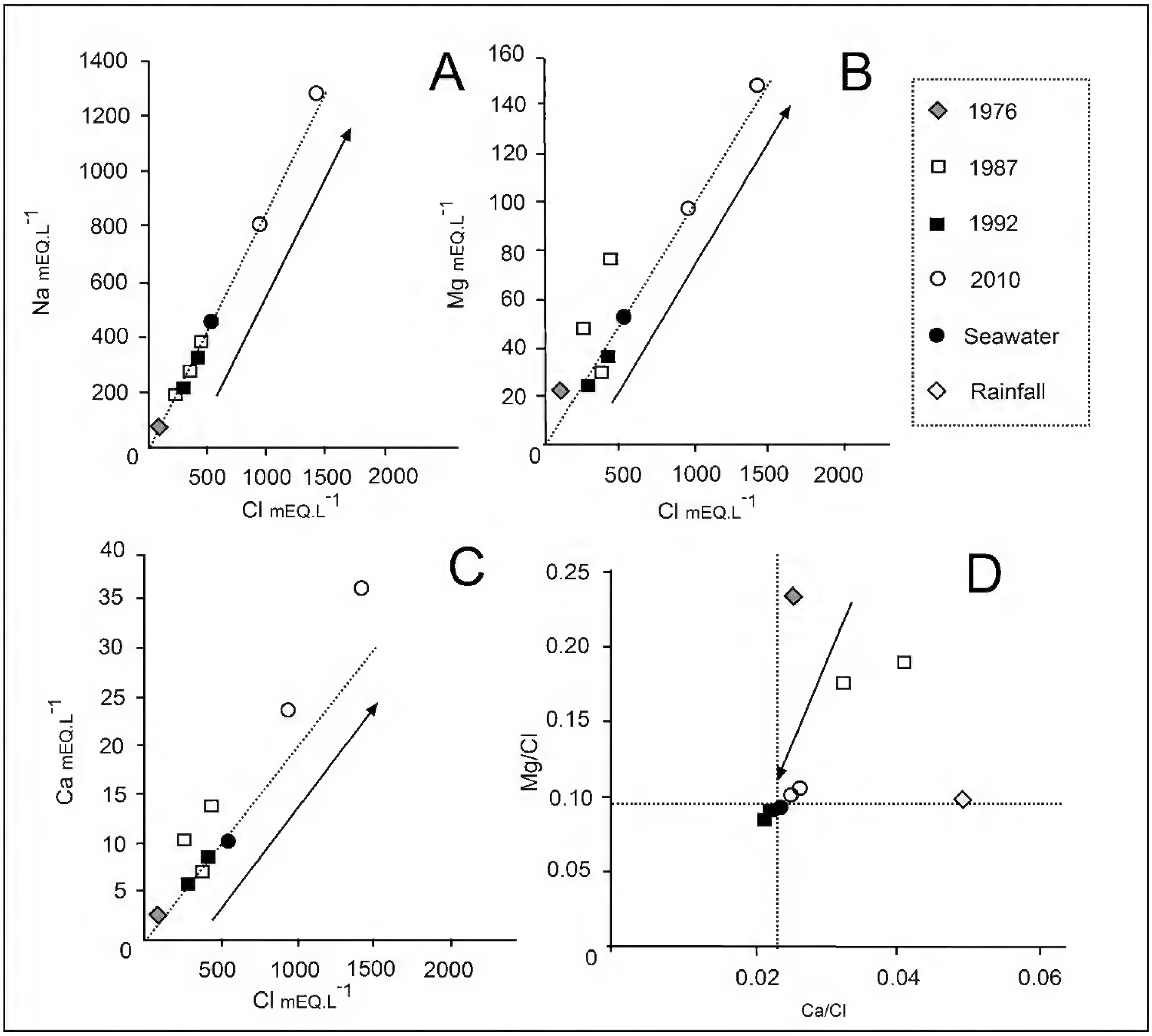

Figure 7. Surface water Na (a), Mg (b) and Ca (c) ionic concentrations versus Cl ionic concentrations (mEq.L^{-1}). Our 2010 data is compared to similar data from 1976 (Williams and Buckley 1976), 1987 (Moore 1987), and 1992 (Rosen *et al* 1996). Mg/Cl versus Ca/Cl ratios (d) for the same data sets are also presented and compared to ratios for rainfall and seawater (Hingston and Gailitis 1976).

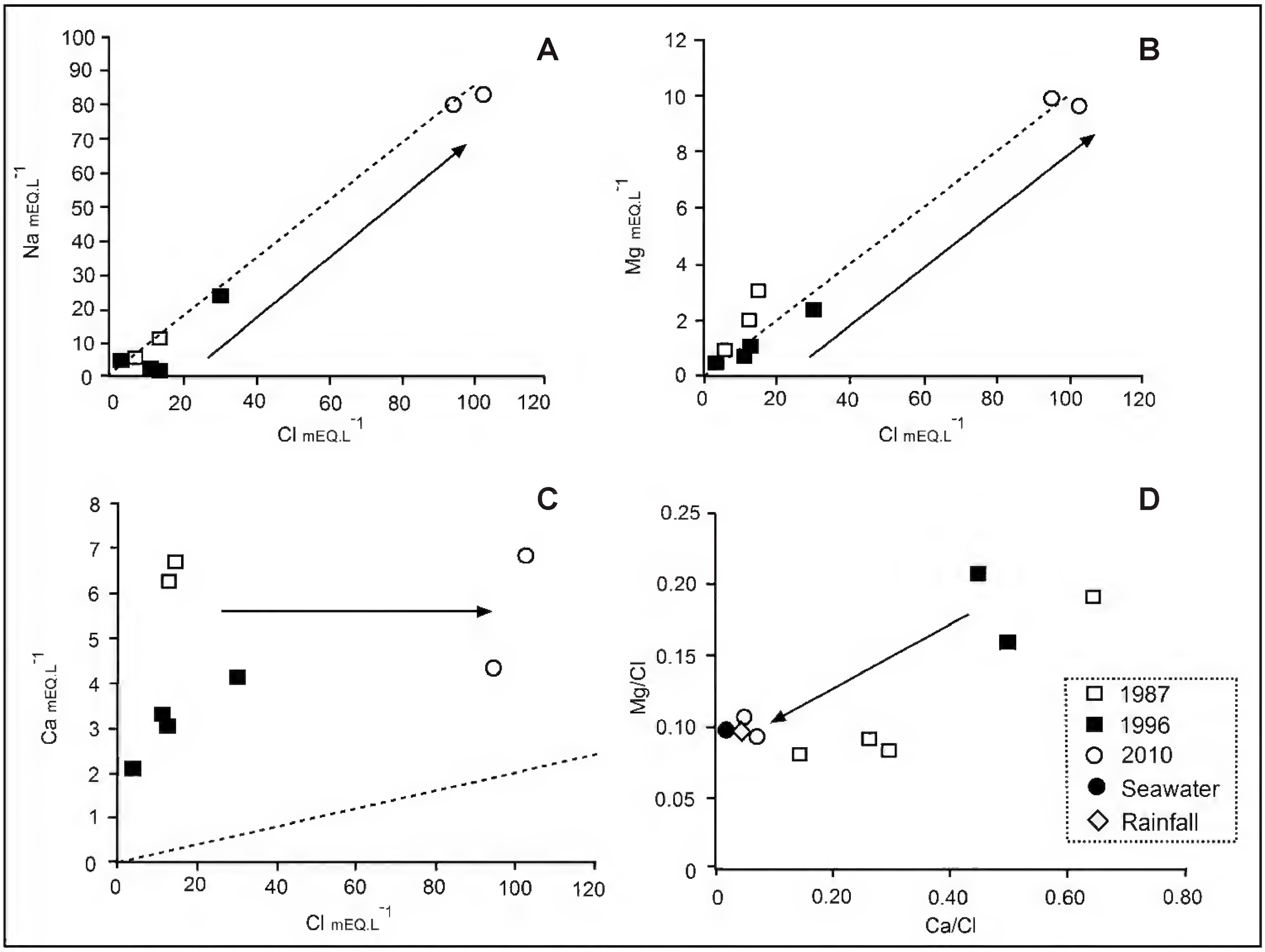

Figure 8. Groundwater (upper fresh water aquifer) Na (a), Mg (b) and Ca (c) ionic concentrations versus Cl ionic concentrations (mEq.L^{-1}). Our 2010 data is compared to similar data for 1987 (Moore 1987) and 1996 (Western Australia Department of Water database 1996). Mg/Cl versus Ca/Cl ratios (d) for the same data sets are also presented and compared to ratios for rainfall and seawater (Hingston and Gailitis 1976).

years where increased rainfall, and subsequent rises in lake levels coincided with a reduction in salinity levels, finding a lack of correlation, with salinity increasing. The rising salinity was attributed to an increase in saline water inflowing to the lake system in comparison to fresh ground water, diluting any effects of variable rainfall. Our data presented here supports the findings by Barr (2003) and Knott *et al* (2003) that changing composition of the upper fresh aquifer groundwater is a key driver in the changing chemical composition of Lake Clifton.

The salinity, δ^2H, δ^{18}O, and ionic data presented here supports the previous studies suggesting that salinity continues to rise in Lake Clifton, reaching levels not previously seen in the last several decades. Our data suggest that groundwater and rainfall associated surface water both continue to contribute to the lake's hydrological composition, however a shift in the chemical composition of the upper fresh aquifer seems likely. It is possible that saline water from the lake (or its underlying salt water interface) could be increasing regional groundwater salinity, however current data sets are insufficient enough to quantify this increase.

Beggs (2014) used a combination of the data presented herein and the long-term data from Lane *et al* (2013) to reconstruct current and predict future water balances of Lake Clifton, identifying insight into the lakes shifting hydrology. The model calculated that lake levels are declining by an average of 0.12 m per year and end-of winter salinity is increasing by 1.2 g/L per year. Total salt mass has increased by 2.5 times since 1985 and total groundwater inflows are estimated to have increased by approximately 40,000 m^3 annually. This combined increase could not be created solely by effects associated with increased abstraction of fresher groundwater and that seawater intrusion from the west is likely to have increased in the last few years, even though this was discounted by Barr (2003).

CONCLUSION

This investigation provides an enhanced understanding of the hydrological functioning of Lake Clifton, on which the existence of the Thrombolite reef located on the eastern edge of the lake relies. Hydro-physical, geochemical and isotopic data for the hydrological system indicate that groundwater and precipitation both contribute to the lakes water balance. Comparisons of our recent data with data sets over the last 20 to 30 years, however suggest that the hydrological balance of the lake, in particular its geochemistry and that of the groundwater infiltrating into its eastern edge has been undergoing alterations during this time frame. It is most likely that a drying climate, increasing temperatures and reduced rainfall, as hypothesized by Barr (2003) are causing a reduction in the amount of freshwater that enters Lake Clifton directly as sub-surface recharge. In turn infiltration of saline groundwater from the Hayward chain of hypersaline lakes to Lake Clifton is creating a redistribution of salt mass from the groundwater system to Lake Clifton (Noble, 2010). This salt was originally concentrated by evaporation in other lakes within the Yalgorup Lakes system and the redistribution of the greater lake system salt balance is ultimately threatening the ecology of this highly significant biodiversity asset and the potability of the upper freshwater local groundwater.

ACKNOWLEDGEMENTS

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Middle Permian (Roadian) Foraminifera from mudstone facies of the type Baker Formation, Southern Carnarvon Basin, Western Australia

DAVID W HAIG [1]*, **ARTHUR J MORY** [2]

[1] *Centre for Energy Geoscience, School of Earth Sciences, University of Western Australia WA 6009, Australia*

[2] *Geological Survey of Western Australia, Department of Mines and Petroleum, 100 Plain Street, East Perth WA 6004, Australia*

* *Corresponding author:* ✉ *david.haig@uwa.edu.au*

Abstract

Foraminifera from the type section of the Baker Formation in the Merlinleigh Sub-basin are recorded for the first time. The sub-basin is part of a marginal rift that splayed from the main East Gondwana interior rift. It was inundated in the Cisuralian (Early Permian) and early Guadalupian (Middle Permian) by a shallow sea with estuarine-like water conditions. The formation forms part of a marine depositional sequence that extends from the uppermost Byro Group to the lower part of the overlying Kennedy Group. Its base is defined by a marine flooding surface and it forms the initial mudstone-dominated retrogradational to early progradational part of the sequence that is considered Roadian (early Guadalupian) in age (ca. 272–269 Ma). The Foraminifera are organic-cemented siliceous agglutinated types belonging to 21 species attributed to *Psammosphaera*, *Thuramminoides*, *Lagenammina*, *Placentammina*, *Psammosiphonella*, *Giraliarella*, *Hyperamminoides*, *Kechenotiske*, *Sansabaina*, *Ammodiscus*, *Hormosinoides*, *Reophax*, *Ammobaculites*, *Spiroplectammina*, *Palustrella* and *Trochamminopsis*. A new species, *Psammosphaera hockingi* n. sp. is described. Changes in assemblage composition through the succession suggest variable environmental conditions (including water depth and salinity) for the carbonaceous muds of this shallow interior sea, similar to those in some modern brackish interior seas and estuaries in temperate humid climatic belts.

KEYWORDS: Siliceous agglutinated Foraminifera; Permian; Merlinleigh Sub-basin; East Gondwana interior rift

INTRODUCTION

The Merlinleigh Sub-basin in the eastern Southern Carnarvon Basin (Fig. 1) contains a continuous Lower Permian to lower Middle Permian marine succession that has long provided a standard stratigraphic reference section for discussion of the Australian upper Paleozoic (Teichert 1941, Condon 1967, Hocking *et al*. 1987, Skwarko 1993, Mory & Backhouse 1997). Within this succession, the mudstone-dominated Baker Formation is the highest formation in the Byro Group, which is characterized by alternating mudstone- and sandstone-dominated units (Fig. 2). The type section of the Baker Formation designated by Condon (1954) lies on a west-facing scarp next to the headwaters of Blackheart Creek on Williambury Station at the northern end of Kennedy Range (Fig. 1b). Elsewhere in the Merlinleigh Sub-basin, the formation has been mapped in scattered exposures, mostly much poorer that the type section, widely separated by faults and large areas lacking outcrop, as well as in three bore sections remote from the type section (Condon 1967, Hocking *et al*. 1987). This has led to some correlations that may not be accurate, particularly when comparing isolated sections to the type section. Additional correlation methods are offered by biostratigraphy, sequence stratigraphy, including an appreciation of palaeobathymetric trends, and climatostratigraphy.

No fossils have been described from the type locality of the Baker Formation apart from a brief mention of the brachiopod "*Chonetes*" at two levels (Condon 1954, 1967). Previous biostratigraphic work on this formation has been undertaken on outcrop and boreholes remote from the type section (Skwarko 1993). Much of the previous work on the formation was done prior to the development of sequence stratigraphy as a method for interpreting outcrop successions (e.g. by Van Wagoner *et al*. 1990); and before an appreciation of East Gondwanan climate trends in different basin settings (see Haig *et al*. 2017). This lack of stratigraphic information has prompted our re-examination of the Baker Formation at its type locality. Our aim is to record the Foraminifera, the most abundant skeletal microfossil group found in the Western Australian Permian, from mudstone facies in this section and to interpret palaeobathymetric trends. This may provide a basis for better correlation of the formation elsewhere.

Geological Setting

During deposition of the Byro Group, the Merlinleigh Sub-basin was part of a shallow interior sea that formed along a narrow rift that splayed from a major rift system through the interior of East Gondwana along what is now the western margin of the Australian continent (East Gondwana interior rift; Haig *et al*. 2017). The interior sea was characterized by a very low gradient seafloor and highly variable water quality influenced by high input of freshwater laden with mud and fine sand. Periodically reduced freshwater inflow allowed the establishment

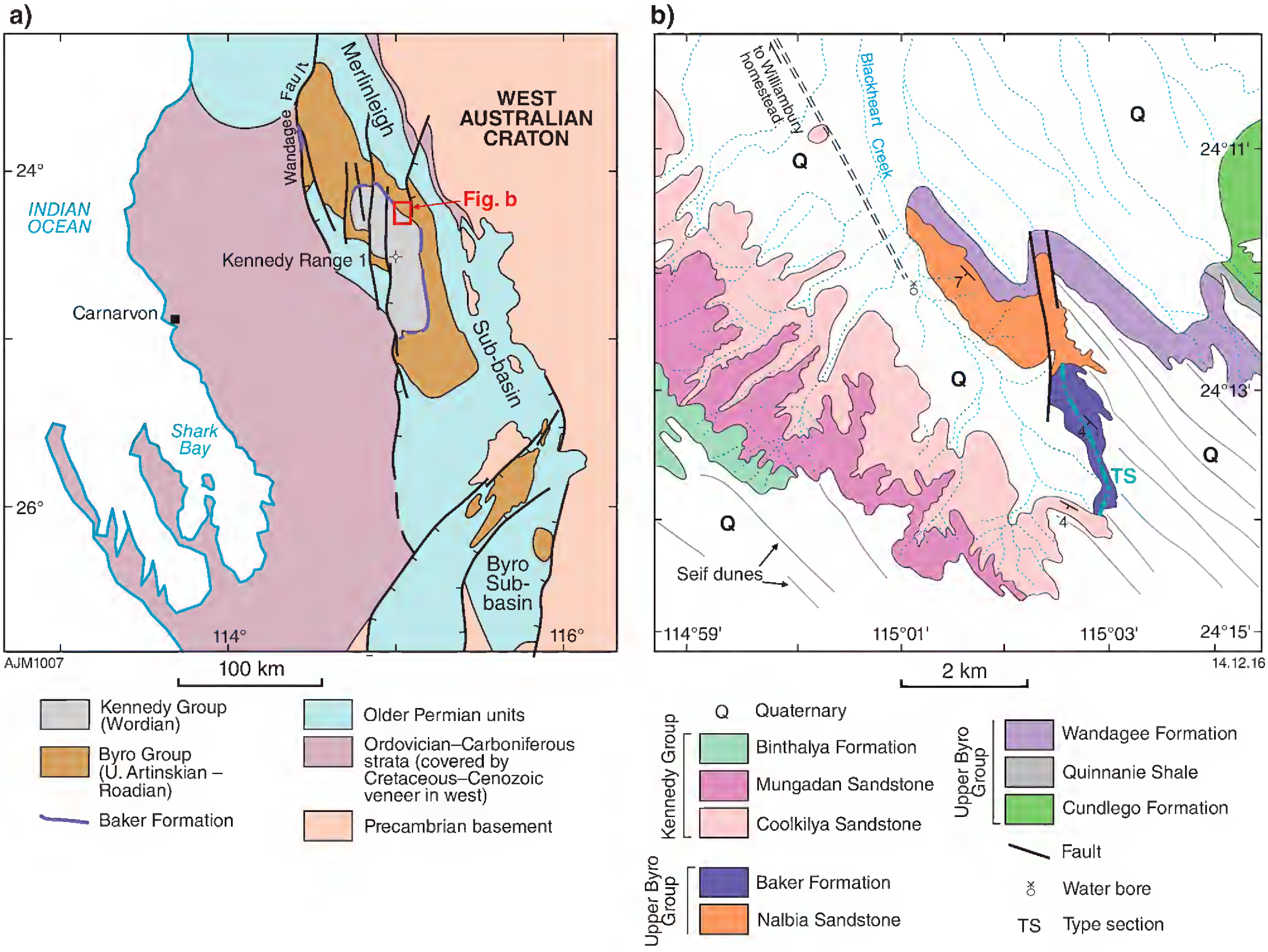

Figure 1. Geological Maps modified from Condon (1967): a) Southern Carnarvon Basin showing the positions of the Merlinleigh and Byro Sub-basins and the extent of the Byro Group within these; b) headwaters of Blackheart Creek showing the location of the type section of the Baker Formation.

Table 1. List of sample localities in type section of Baker Formation.

Sample	°S	°E	Location description
S1	24.22437	115.04791	1.7 m above base of formation; dark grey sandy mudstone with rare small bivalves
S2	24.22437	115.04791	3.4 m above base of formation; sandy mudstone with small scale bioturbation (sand-infilled burrows); jarositic layers
S3	24.22437	115.04791	5.1 m above base of formation; sandy blue-grey mudstone with small "pectens"
S4	24.22437	115.04791	10.5 m above base of formation, dark grey mudstone some sand laminae; about 0.3 m above 0.5 m thick mainly sandstone unit.
S5	24.22437	115.04791	12 m above base of formation; dark grey mudstone
S6	24.22437	115.04791	15 m above base of formation; dark grey mudstone
S7	24.22437	115.04791	16.8 m above base of formation; sandy mudstone
S8	24.22437	115.04791	18.7 m above base of formation; sandy mudstone
S9	24.22437	115.04791	20 m above base of formation; 20 cm above 40 cm-thick sandstone which is laminated at top and contains scattered Skolithos burrows
S10A,B	24.23028	115.04987	from mudstone unit about 2 m below contact with Coolkilya Sandstone

of normal-marine conditions and faunas, but restricted brackish water with estuarine-like conditions, similar to those in the present-day Baltic Sea, prevailed during deposition of most of the Byro Group (Haig 2003, 2004, Haig *et al.* 2014, 2017).

Material and methods

Along the scarp at the type locality (Figs. 1b, 3), no one vertical section transects the entire Baker Formation which dips at about 4° to the southwest. The Coolkilya Sandstone conformably overlies the southern part of the section whereas along most of the scarp the formation is overlain unconformably by flat-lying Cenozoic sandstone or is obscured by scree from this sandstone. For this study, the stratigraphic section was compiled by measuring the thickness of the basal mudstone unit using an abney level and then estimating the thicknesses of overlying units with the help of a series of photographs taken along the scarp.

Friable mudstone samples (Table 1) were collected after digging into the outcrop to obtain the freshest possible material. In the laboratory, samples were disaggregated by boiling in water with added detergent and then washed over 2 mm and 150 µm sieves. The residues collected from these sieves were examined under reflected light using a stereomicroscope and foraminifera picked onto microfossil-sorting slides using a damp very fine (000) sable-hair brush. Selected specimens were photographed under reflected light using an Olympus BX51 microscope. For each specimen a series of images was taken at slightly different focal lengths and the final image rendered using the depth-map method in the Helicon Focus 4.2.9 program. The microfossils and unprocessed portions of each rock sample are housed in the collections of the Edward de Courcy Clarke Earth Science Museum at the University of Western Australia.

TYPE SECTION STRATIGRAPHY

Lithostratigraphy

The base of the Baker Formation at the type section (Figs. 3b, 4) is at a friable sandy mudstone bed that overlies a more indurated quartz sandstone unit (72 m thick) that was designated by Condon (1954, 1967) as the type section of the "Norton Greywacke", but has since been referred to Teichert's (1950, 1957) Nalbia Sandstone (McWhae *et al.* 1958; Dickins 1963). The stratigraphic top of the Baker Formation (Figs. 3d, 4) is present at the southern end of the type-section scarp where it was defined as the highest mudstone overlain by thick quartz sandstone of the overlying "Coolkilya Greywacke" (Condon 1954, 1967; = Coolkilya Sandstone of Teichert 1950).

Although all stratigraphic logs compiled for the type section show three main stratigraphic divisions including a lower unit of mostly carbonaceous mudstone, a middle

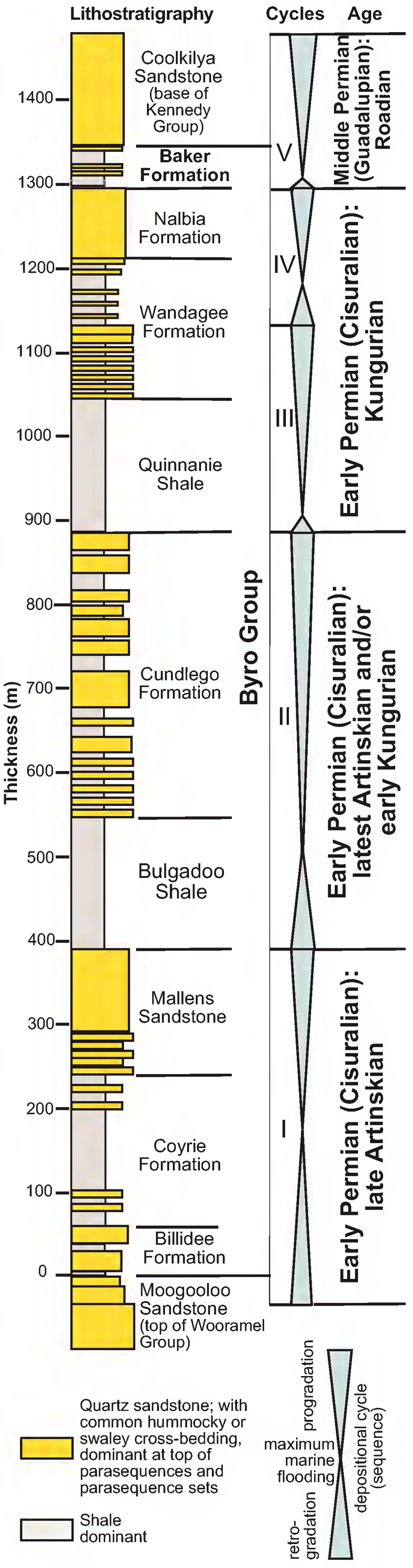
Lithostratigraphy
Cycles
Age
Thickness (m)
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Coolkilya Sandstone (base of Kennedy Group)
Baker Formation
Nalbia Formation
Wandagee Formation
Quinnanie Shale
Cundlego Formation
Bulgadoo Shale
Mallens Sandstone
Coyrie Formation
Billidee Formation
Moogooloo Sandstone (top of Wooramel Group)
Byro Group
V
IV
III
II
I
Middle Permian (Guadalupian): Roadian
Early Permian (Cisuralian): Kungurian
Early Permian (Cisuralian): latest Artinskian and/or early Kungurian
Early Permian (Cisuralian): late Artinskian
Quartz sandstone; with common hummocky or swaley cross-bedding, dominant at top of parasequences and parasequence sets
Shale dominant
progradation
maximum marine flooding
retro-gradation
depositional cycle (sequence)

Figure 2. Schematic stratigraphic log of the Byro Group (modified from Haig *et al.* 2017) showing the succession of formations, depositional cycles and ages.

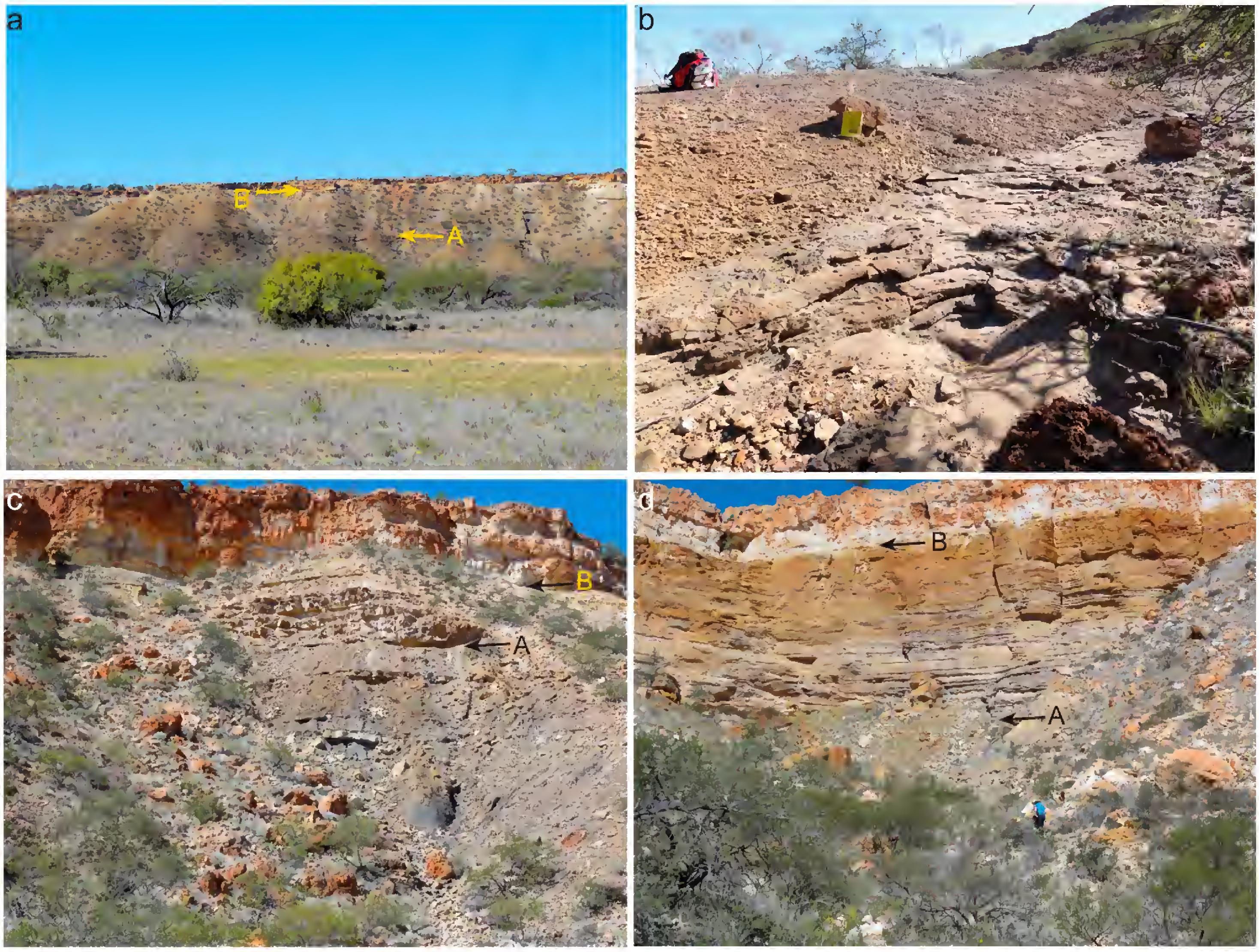

Figure 3. Outcrop photographs of parts of the type section of the Baker Formation: a) western-facing scarp (A, base of Baker Formation; B, unconformable contact with overlying Cenozoic sandstone); b) base of Baker Formation at marine flooding surface between underlying sandstone of the Nalbia Sandstone and overlying sandy mudstone of the Baker Formation; c) lower part of Baker Formation (A, boundary between lower mudstone unit containing several sandstone interbeds, and middle sandstone unit; B, unconformable contact with overlying Cenozoic Sandstone); d) north-facing scarp: (A, conformable contact between Baker Formation and overlying Coolkilya Sandstone; B, unconformable contact with overlying Cenozoic sandstone).

sandstone unit, and an upper unit of mainly mudstone, the stratigraphic thicknesses measured vary. Condon (1954, 1967) measured 60 m of strata forming the type section; Moore *et al*. (1980a) determined 52 m; we estimate a thickness of about 42 m (Fig. 4).

Friable sandy mudstone at the base of our measured section (Fig. 3b) contains calcareous spherical nodules, 2–4 cm in diameter, formed around pectinacean bivalves (now preserved as moulds). The lower mud-dominated unit (Fig. 3c) extends to 22 m above the base of the section and includes three sandstone beds with swaley and parallel laminations, each less than 50 cm thick, at about 9 m, 15 m and 19 m above the formation base. The mudstone adjacent the sandstone is sandy but elsewhere is dark-grey with a very minor sand component consisting mainly of quartz grains and siliceous agglutinated Foraminifera. No calcareous mudstone nodules were observed in the section, nor are there calcareous shell material or skeletal grains – extremely rare bivalve fossils are preserved as internal and external moulds as the original very thin calcareous shells have been dissolved.

The middle unit, 22 m to about 37 m above the formation base, contains medium to thick quartz sandstone beds (Figs. 3c, 4). These were not sampled because well-sorted quartz sandstone usually lacks Foraminifera. Condon (1954, 1967) recorded a very thin "*Chonetes* coquinite" in mid-section of the unit. The upper unit includes a few metres of grey mudstone beneath the quartz sandstone succession of the Coolkilya Sandstone (Figs. 3d, 4).

Foraminiferal Biostratigraphy

Foraminifera are present in all the studied mudstone samples and are the only biogenic grains in the >150 μm washed sand component of each sample (Table 2). They are siliceous agglutinated species that originally constructed a test with siliciclastic grains (mainly quartz) held together by organic (glycoproteinaceous)

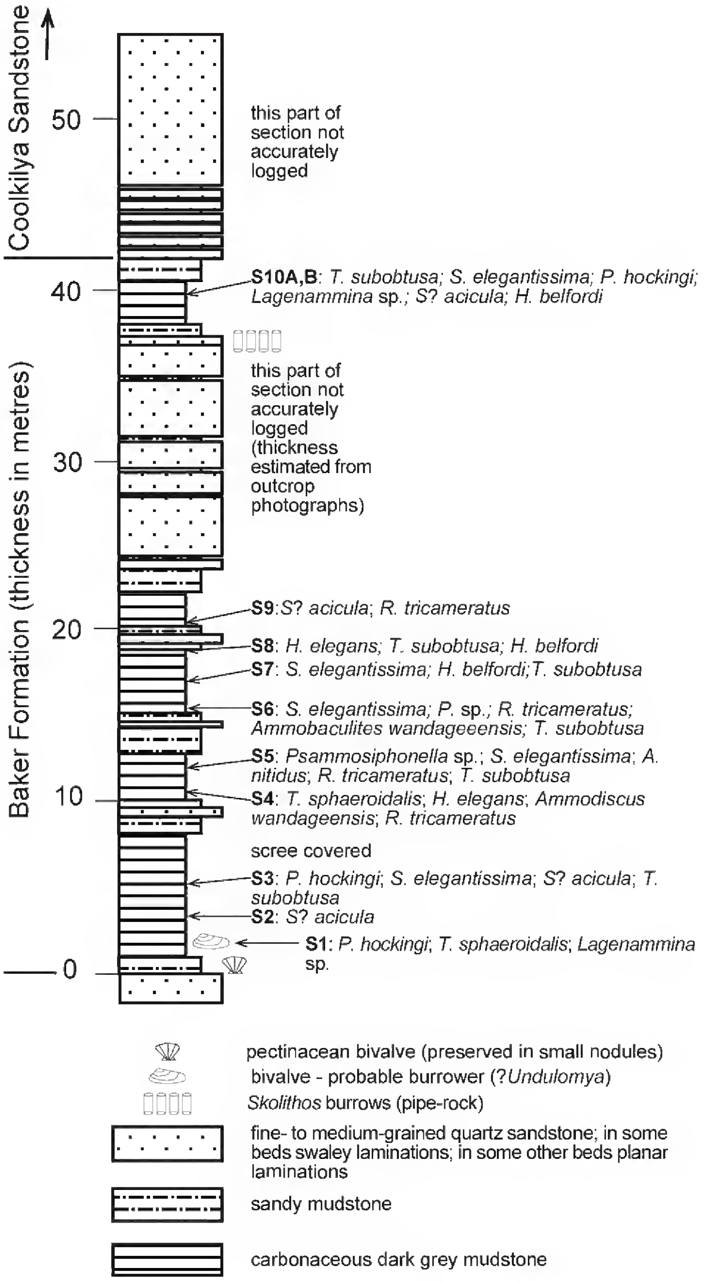
Coolkilya Sandstone
Baker Formation (thickness in metres)
50
40
30
20
10
0
this part of section not accurately logged
S10A,B: T. subobtusa; S. elegantissima; P. hockingi; Lagenammina sp.; S? acicula; H. belfordi
this part of section not accurately logged (thickness estimated from outcrop photographs)
S9: S? acicula; R. tricameratus
S8: H. elegans; T. subobtusa; H. belfordi
S7: S. elegantissima; H. belfordi; T. subobtusa
S6: S. elegantissima; P. sp.; R. tricameratus; Ammobaculites wandageeensis; T. subobtusa
S5: Psammosiphonella sp.; S. elegantissima; A. nitidus; R. tricameratus; T. subobtusa
S4: T. sphaeroidalis; H. elegans; Ammodiscus wandageensis; R. tricameratus
scree covered
S3: P. hockingi; S. elegantissima; S? acicula; T. subobtusa
S2: S? acicula
S1: P. hockingi; T. sphaeroidalis; Lagenammina sp.
pectinacean bivalve (preserved in small nodules)
bivalve - probable burrower (?Undulomya)
Skolithos burrows (pipe-rock)
fine- to medium-grained quartz sandstone; in some beds swaley laminations; in some other beds planar laminations
sandy mudstone
carbonaceous dark grey mudstone

Figure 4. Stratigraphic log of type section of Baker Formation showing the positions of studied samples and the dominant foraminiferal species in each sample.

cement. During burial diagenesis, the flexible test deflates and deforms in various ways and the organic cement degrades. Over time, secondary quartz cement precipitates as interlocking quartz overgrowths on the silicate grains forming a rigid siliceous shell. Some of the tests originally had an organic inner lining and this seems still to be preserved in the initial whorls of some of the *Trochamminopsis* and *Palustrella*. These Foraminifera were very conservative in their evolution, with many genera ranging from the late Paleozoic through to the Cenozoic (Haig & McCartain 2010). No calcareous Foraminifera are present in the studied samples. It is possible that calcareous species were originally present in the life environment but their tests may have dissolved in the carbonaceous mud on the seafloor before substantial burial.

Within the Byro Group, siliceous agglutinated Foraminifera are the most abundant and persistent of any fossil group with mineralized skeletons (Parr 1942, Crespin 1958, Belford 1968, Palmieri 1993, Haig 2003, 2004, Haig *et al.* 2017). Frequent changes in foraminiferal assemblages noted by Haig (2003) and Haig *et al.* (2017) relate to high-frequency environmental changes with similar assemblages reappearing when comparable conditions returned to the depositional site. However, some broader biostratigraphic changes are also evident in the faunal distribution patterns that may be significant for stratigraphic correlation within the basin and between adjacent basins.

The foraminiferal fauna recovered from the type Baker Formation comprises 21 species (Table 2) and can be compared with assemblages listed by Haig *et al.* (2017) from formations of depositional cycles 1–3 of the Byro Group (Billidee Formation to lower Wandagee Formation) and the illustrated assemblages of Parr (1942), Crespin (1958), Belford (1968), Foster et al. (1985), Haig (2003), and Dixon & Haig (2004). Assemblages from depositional cycle 4 that includes the upper Wandagee Formation and Nalbia Sandstone (= Norton Greywacke), immediately below the Baker Formation, are very poorly known. All species from the Baker Formation but one are known from lower formations. The exception is *Hormosinoides* sp. cf. *H. expatiatus*, represented here by very few specimens. The recorded Western Australian distributions of the other species are listed in the RECORD OF FORAMINIFERA in this paper and are being revised in our continuing studies.

Comparison of successive assemblages in the type section (Table 2) suggests faunal composition changed frequently. Based on presence or absence of species, similarities range from 27% between samples S1 and S3 to 58% between S7 and S8. Dominant species also change from sample to sample (Fig. 4). Similar high-frequency changes are present in the older Quinnanie Shale of depositional cycle 3, based on comparison of assemblages taken at 1 m intervals through a >190 m-thick mudstone succession (Haig 2003). The variability in faunal composition in the Baker Formation type section indicates that biostratigraphic comparisons for correlation purposes should be based on a series of samples, collected in the context of the sequence stratigraphy (see below) rather than a single sample.

Sequence stratigraphy

Based on broad patterns of retrogradation (i.e. marine transgression) and progradation (i.e. shallowing of marine conditions), Haig *et al.* (2017) recognized five major depositional cycles in the Byro Group (Fig. 2). The Baker Formation represents the initial retrogradational phase, maximum marine flooding interval and initial progradational phase of cycle 5, which incorporated the lower part of the overlying Coolkilya Sandstone as a late progradational stage. The base of the Baker Formation is a marine flooding surface initiated by an increase in water depths to below storm-wave base. The top of the Baker Formation at the transition from the uppermost mudstone to sandstone is indicative of shoaling to water depths consistently above fair-weather wave base. This boundary is conformable, as also recognized by Hocking *et al.* (1987), within a consistent progradational trend.

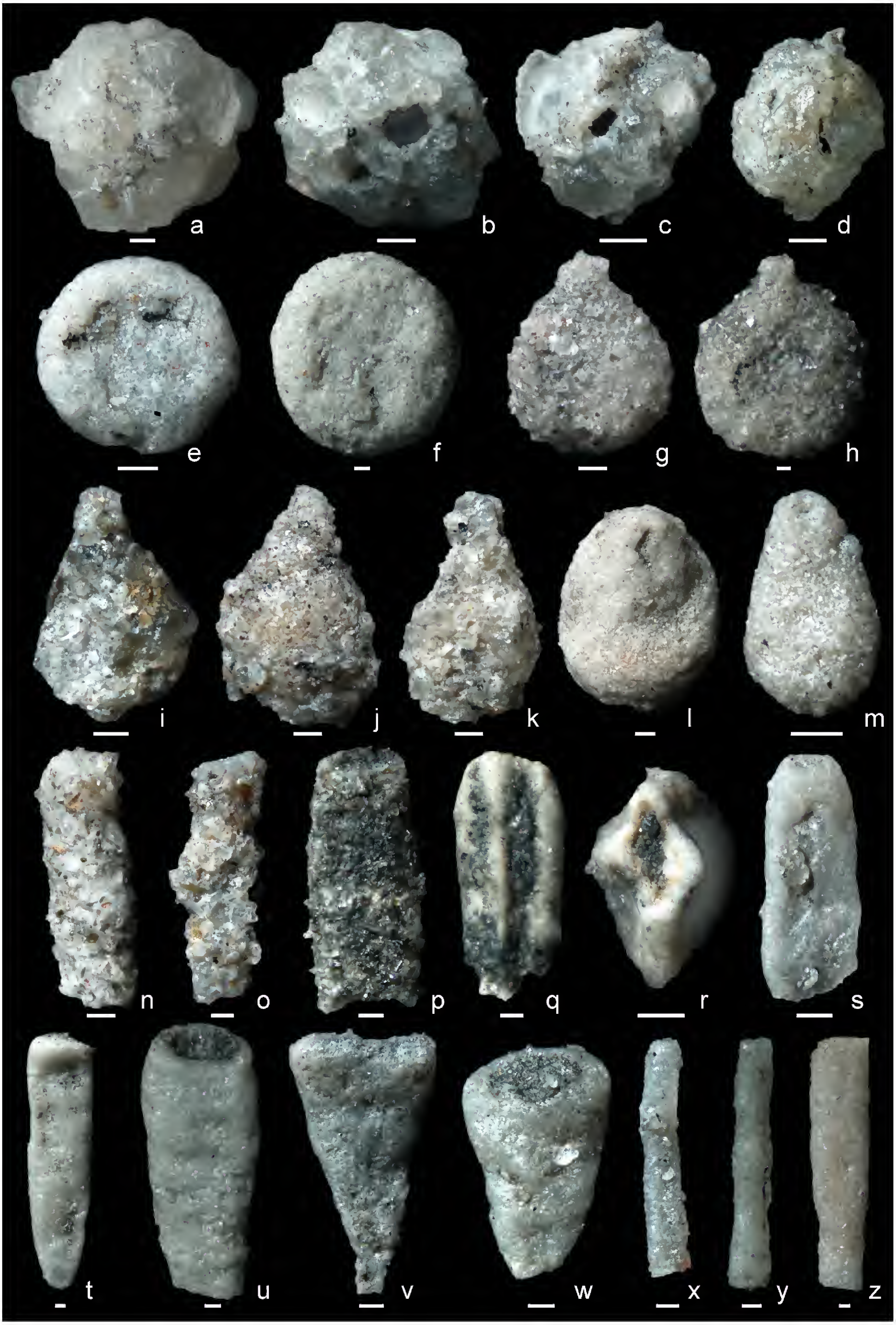
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Figure 5. Foraminiferal images taken under reflected light and rendered from a series of photographs taken at slightly different focal lengths (bar scale = 0. 1 mm). a–d *Psammosphaera hockingi* n. sp.: a, paratype, UWA172000, S3 from 5.1 m above base of Baker Formation; b, holotype, UWA172001, S10A from ~ 2m below top of Baker Formation; c, paratype, UWA172002, S5 from 12 m above base of Baker Formation; d, paratype, 172003, S10A from ~ 2m below top of Baker Formation. e, f *Thuramminoides sphaeroidalis* Plummer 1945: e, hypotype, UWA172004, S1 from 1.7 above base of Baker Formation; f, hypotype, UWA172005, S3 from 5.1 m above base of Baker Formation. g–k *Lagenammina* sp.; g, hypotype, UWA172006, S4 from 10.5 m above base of Baker Formation; h, hypotype, UWA172007, S1 from 1.7 above base of Baker Formation; i, hypotype, UWA172008, sample S4 from 10.5 m above base of Baker Formation; j, hypotype, UWA172009, sample S5 from 12 m above base of Baker Formation; k, hypotype, UWA172010, sample S5 from 12 m above base of Baker Formation. l, m *Placentammina ampulla* (Crespin 1958): l, hypotype, UWA172011, sample S5 from 12 m above base of Baker Formation; m, hypotype, UWA172012, S5 from 12 m above base of Baker Formation. n–p *Psammosiphonella* sp.: n, hypotype, UWA172013, S5 from 12 m above base of Baker Formation; o, hypotype, UWA172014, S5 from 12 m above base of Baker Formation; p, hypotype, UWA172015, S4 from 10.5 m above base of Baker Formation. q, r *Giraliarella rhomboidalis* Crespin 1958: q, hypotype, UWA172016, S3 from 5.1 m above base of Baker Formation; r, hypotype, UWA172017 sample S3 from 5.1 m above base of Baker Formation. s, t *Hyperamminoides elegans* (Cushman and Waters 1928): s, hypotype, UWA172018, sample S1 from 1.7 above base of Baker Formation; t, hypotype, 172019, sample S8 from 18.7 m above base of Baker Formation. u *Kechenotiske hadzeli* (Crespin 1958), hypotype, UWA172020, sample S4 from 10.5 m above base of Baker Formation. v, w *Kechenotiske expansa* (Plummer 1945): v, hypotype, UWA172021, sample S10A from ~ 2m below top of Baker Formation; w, hypotype, UWA172022, sample S6 from 15 m above base of Baker Formation. x, y *Sansabaina elegantissima* (Plummer 1945): x, hypotype, UWA172023, S4 from 10.5 m above base of Baker Formation; y, hypotype, UWA172024, sample S3 from 5.1 m above base of Baker Formation. z *Sansabaina*? *acicula* (Parr 1942), hypotype, UWA172025, S3 from 5.1 m above base of Baker Formation.

Table 2. Distribution of Foraminifera in studied samples from type section of Baker Formation

VR = single specimen; R = 2-5; C = 6-10; A = >10 specimens	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10 A**	**S10 B**
Psammosphaeridae											
Psammosphaera hockingi n. sp.	C	VR	C	R	VR		R	R		A	R
Thuramminoides sphaeroidalis Plummer	C	VR	R	A		VR				R	
Saccamminidae											
Lagenammina sp.	C	VR		R	R	R			VR	R	C
Placentammina ampulla (Crespin)					R						
Bathysiphonidae											
Psammosiphonella sp.		VR		R	C	C	R	R	R		R
Hyperamminoididae											
Giraliarella rhomboidalis Crespin			R				VR			VR	
Hyperamminoides elegans (Cushman and Waters)	R		R	C	VR	R	?	A	R	?	?
Kechenotiske expansa (Plummer)						R			R	R	
Kechenotiske hadzeli (Crespin)	VR		VR	VR							
Sansabaina elegantissima (Plummer)	R		C		C	A	C	R	A	C	A
Sansabaina? acicula (Parr)	R	C	C			R	R		C	C	R
Ammodiscidae											
Ammodiscus erugatus Crespin	R		VR	R							VR
Ammodiscus nitidus Parr				R	C		VR			R	
Ammodiscus wandageeensis Parr	R			C		?	R	VR	R	R	R
Hormosinidae											
Hormosinoides belfordi (Crespin)	R	VR	R		VR	R	C	C		C	R
Hormosinoides sp. cf. *H. expatiatus* Plummer		VR									VR
Reophax tricameratus Parr	R	R		C	C	C		R	C		
Haplophragmoididae											
Ammobaculites wandageensis Crespin	R			R		C					
Spiroplectamminidae											
Spiroplectammina carnarvonensis (Crespin						VR		VR	VR		
Verneuilinoididae											
Palustrella improcera (Crespin)	VR	R									
Trochamminidae											
Trochamminopsis subobtusa (Parr)			C		C	C	C	A		A	A
Similarity % with next highest sample (based on presence/absence)	38	27	29	44	47	41	58	50	38	44	

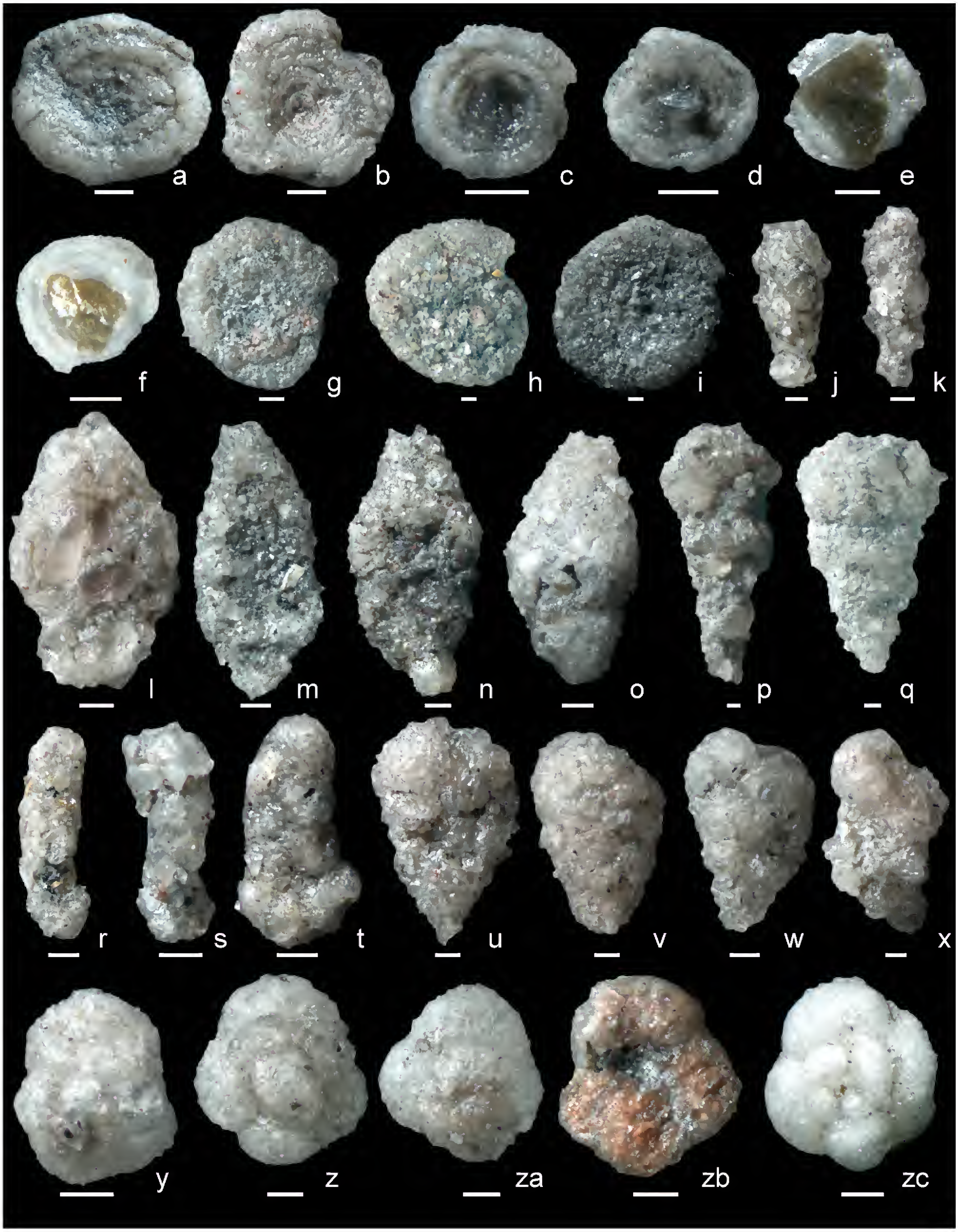
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Figure 6. Foraminiferal images taken under reflected light and rendered from a series of photographs taken at slightly different focal lengths (bar scale = 0. 1 mm). a, b *Ammodiscus erugatus* Crespin 1958; a, hypotype, UWA172026, S3 from 5.1 m above base of Baker Formation; b, hypotype, UWA172027, S1 from 1.7 above base of Baker Formation. c–f *Ammodiscus nitidus* Parr 1942; c, hypotype, UWA172028, S4 from 10.5 m above base of Baker Formation; d, hypotype, UWA172029, S4 from 10.5 m above base of Baker Formation; e, hypotype, UWA172030, S4 from 10.5 m above base of Baker Formation; f, hypotype, UWA172031, S10A from ~ 2m below top of Baker Formation. g–i *Ammodiscus wandageeensis* Parr 1942; g, hypotype, UWA172032, S1 from 1.7 above base of Baker Formation; h, hypotype, UWA172033, S1 from 1.7 above base of Baker Formation; i, hypotype, UWA172034, S4, from 10.5 m above base of Baker Formation. j, k *Hormosinoides belfordi* (Crespin 1958); j, hypotype, UWA172035, S1 from 1.7 above base of Baker Formation; k, hypotype, UWA172036, S1 from 1.7 above base of Baker Formation. l–o *Reophax tricameratus* Parr 1942; l, hypotype, UWA172037, S1 from 1.7 above base of Baker Formation; m, hypotype, UWA172038, S4 from 10.5 m above base of Baker Formation; n, hypotype, UWA172039, S4 from 10.5 m above base of Baker Formation; o, hypotype, UWA172040, S5 from 12 m above base of Baker Formation. p, q *Hormosinoides* sp. cf. *H. expatiatus* (Plummer 1942); p, hypotype, UWA172041, S2 from 3.4 m above base of Baker Formation; q, hypotype, UWA172042, S10A from ~ 2m below top of Baker Formation. r, s *Ammobaculites wandageensis* Crespin 1958; r, hypotype, UWA172043, S1 from 1.7 above base of Baker Formation; s, hypotype, UWA172044, S4 from 10.5 m above base of Baker Formation. t *Spiroplectammina carnarvonensis* Crespin 1958, hypotype, UWA172045, S6 from 15 m above base of Baker Formation. u–x *Palustrella improcera* (Crespin 1958); u, hypotype, UWA172046, S1 from 1.7 above base of Baker Formation; v, hypotype, UWA172047, S2 from 3.4 m above base of Baker Formation; w, hypotype, UWA172048, S2 from 3.4 m above base of Baker Formation; x, hypotype, UWA172049, S2 from 3.4 m above base of Baker Formation. y–zc *Trochamminopsis subobtusa* (Parr 1942); y, hypotype, UWA172050, S5 from 12 m above base of Baker Formation; z, hypotype, UWA172051, S8 from 18.7 m above base of Baker Formation; za, hypotype, UWA172052, S8 from 18.7 m above base of Baker Formation; zb, hypotype, UWA172053, S3 from 5.1 m above base of Baker Formation; zc, hypotype, UWA172054, S5 from 12 m above base of Baker Formation.

Whereas Condon (1954, 1967) interpreted the boundary as disconformable and "in places unconformable", Moore *et al.* (1980b) pointed out that the supposed erosion at this level (near the southern end of Kennedy Range) is along a faulted contact.

Higher frequency cycles are evident in the type section. Moore *et al.* (1980a) and Hocking *et al.* (1987) recognized two main mudstone–sandstone cycles and these are apparent in our measured section (Fig. 4). The presence of interbedded sandstone with swaley cross-bedding within the mudstone units and the frequent up-sequence changes in foraminiferal assemblages suggest higher frequency depositional cyclicity. More closely spaced sampling for Foraminifera, such as done by Haig (2003) for the Quinnanie Shale, is required before the cyclic pattern can be fully understood and to determine the positions of maximum flooding intervals in each of the cycles. Based on the foraminiferal palaeobathymetric model established by Haig (2003) for the Quinnanie Shale, the deepest water intervals probably incorporate the levels of S1–S3, S5, S6–S7, S9 and S10. These contain an association of *Sansabaina elegantissima* and *Lagenammina hemisphaerica* found only in the "Lower Offshore Zone" of the Quinnanie-Shale model.

Age determination

Because of the very conservative nature of the morphologies of the foraminiferal genera (Haig & McCartain 2010) and their long time ranges, the siliceous agglutinated types from the Baker Formation cannot be used for correlation to the international chronostratigraphic scheme (GTS v. 2016.12; www. stratigraphy. org). The age of the Baker Formation relies on the presence of ammonoids within depositional cycle 5 at localities away from the type section.

Much discussion has centred on the stratigraphic positions of the ammonoids *Daubichites goochi* (Teichert), *Agathiceras applanatum* Teichert, *Popanoceras* sp., and *Paragastrioceras wandageense* Teichert (see Teichert 1941, 1944, Glenister & Furnish 1961, Cockbain 1980, Archbold & Dickins 1989, Archbold 1998). Although Teichert (1941, 1944) was confident that all the genera were from his "*Linoproductus* stage" their precise localities are now uncertain, and it is possible that some of the rare specimens came from scree that may have moved from their original stratigraphic position. His local stage nomenclature preceded the code of lithostratigraphic nomenclature formulated in the 1950s that was followed in later geological mapping in the region (e.g. Condon 1954, 1967). A diverse fossil assemblage characterizes the "*Linoproductus* stage" including Bryozoa, crinoids (*Calceolspongia*), various brachiopods including the *Linoproductus* of Teichert (placed within *Cancrinella* by Archbold 1983), and bivalves. The stage was underlain by a stratigraphic interval with relatively sparse assemblages dominated by bivalves (the *Schizodus* stage of Teichert 1941). It is clear that the fauna of the "*Linoproductus* stage" comes from fossiliferous beds found at widespread localities in the lower part of the Coolkilya Sandstone (see compilation of Skwarko 1993, and stratigraphic logs of Condon 1967). As discussed by Leonovo (2011) *Daubichites* is indicative of the Roadian Stage of the Guadalupian Series (Middle Permian, 268.8±0.5 – 272.95±0.11 Ma, GTS v 2016/12). In the absence of any other age information, depositional cycle 5, including the Baker Formation, is placed within the Roadian.

Organic geochemistry

Four of the 10 samples (S1, S5–7) were analysed and yielded moderate total organic carbon values (TOCs) of 1.04 – 2.23%. RockEval data shows: (1) the pyrogram peak "S_2" at a low 0.10 – 0.22 mg/gm rock, a parameter recording the volume of hydrocarbons that formed during thermal pyrolysis of the sample and a measure of the amount of hydrocarbons that still may be produced if thermal maturation continues; (2) the hydrogen index "HI" at a very low 5–10, calculated from 100 x S_2/TOC, indicating the potential to generate oil and reflecting the type of organic material (kerogen) in the rock; and (3) the oxygen index OI at 60–66, calculated from 100 x S_3/TOC where peak "S_3" on the pyrogram measures the amount of CO_2 emitted during thermal breakdown of the kerogen (McCarthy *et al.* 2011). These values suggest that the organic content either has been greatly affected by weathering or that the original depositional environment was dominated by decomposed plant material—either reason could explain the lack of calcareous foraminifera in this section. Our results suggest the poor values from about this level in Kennedy Range 1, the only well from which analyses of the upper Byro Group are available, are not necessarily a good indication of the hydrocarbon generating potential of the upper part of the group. Further drilling is required to provide unweathered samples to properly evaluate the potential of this interval.

One sample (S5) analysed for vitrinite reflectance yielded a mean value of 0.55% indicating the section lies above the early oil-generating window with burial unlikely to have exceeded 1 km, of which at least half can be accounted for by the overlying 550–750 m thick Middle Permian Kennedy Group (Hocking *et al.* 1987). This amount of burial is relatively low thereby suggesting relatively low compression of mudstone in the Baker Formation consistent with the well-preserved, at least partially inflated, foraminiferal tests.

DEPOSITIONAL ENVIRONMENT

Haig (2004) and Haig *et al.* (2017) interpreted the depositional setting of the Byro Group as a narrow, shallow, interior sea with a very low-gradient seafloor and lacking a shelf to basin topography. The absence of a shelly marine fauna in much of the sand facies, except in relatively few isolated beds, and the abundance and diversity of siliceous agglutinated Foraminifera in carbonaceous muds deposited below wave base suggest an interior sea with estuarine-like environments such as in the present-day Baltic Sea (Kunzendorf & Larsen 2002; Haig 2003, 2004). At times salinity may have fluctuated depending on variable inflow of freshwater. Because of the narrow wave-fetch environment, fair-weather and storm-wave bases (i.e., the mud–sand interface on the seafloor) may have been very shallow (e.g. a few metres).

Within the carbonaceous mud facies of the Baker Formation, the persistent high abundance and relative high diversity (compared to the fauna known elsewhere in the Byro Group) of siliceous agglutinated Foraminifera and the very sparse thin-shelled macrofauna (bivalves) suggest that hyposaline conditions prevailed during deposition. The large robust foraminiferal tests (Figs. 5, 6) indicate that the seafloor was above the anaerobic zone. Changes in faunal composition through the mudstone section may have been caused by a complex interplay of environmental factors including fluctuations in water depth, turbidity, acidification of bottom water because of variable carbonaceous content, as well as dissolved oxygen and salinity. A better understanding of these factors will only be gained through more detailed study of the Baker Formation at this and other localities as well as similar studies of other formations in the Byro Group.

RECORD OF FORAMINIFERA

Family Psammosphaeridae Haeckel 1894

Genus *Psammosphaera* Schulze 1875

Type species: *Psammosphaera fusca* Schulze 1875.

Psammosphaera hockingi n. sp.; Figs. 5a–d.

2004 *Psammosphaera* sp. 1, Dixon & Haig, p. 320, pl. 2, figs. 7, 8.

Type material: Holotype, UWA172001, Fig. 5b, from S10A about 2 m below top of Baker Formation at type section (Fig. 4).

Derivation of name: Named in honour of Roger Hocking for his contributions to understanding the stratigraphy and sedimentology of the Byro Group, including the Baker Formation.

Diagnosis: A Permian species of *Psammosphaera* with test diameter to at least 0.83 mm; coarsely agglutinated wall with very rough surface composed of a mosaic of few angular to subangular quartz grains up to at least 540 μm diameter that are among the coarsest of any grains incorporated in the agglutinated tests of the accompanying foraminiferal assemblage; one or two variable openings in some tests.

Description: Test usually inflated with little deformation compared to the tests of accompanying species; globular, up to at least 0.83 mm in diameter, with very rough surface. Wall composed of a mosaic of angular to subangular quartz grains with a few larger grains up to at least 0.83 mm in diameter forming most of the surface and with finer grains packed in the interstices between the large grains. Some tests have one or two openings that are slit-shaped, oval, or approximately circular in outline. No apertural neck or distinct lip is developed.

Comparisons: The coarse-grained *Proteonina arenosa* Crespin (1958, p. 38, pl.2, figs. 6, 7), from the Byro Group in the Merlinleigh and Byro Sub-basins, differs in having an "apertural protuberance". *Psammosphaera pusilla* Parr (1942, p. 106, pl.1, figs. 6, 7) differs with a much finer grained agglutinated wall.

Previous illustrated Western Australian records: Dixon & Haig (2004 as *Psammosphaera* sp.; Carrandibby Formation, Byro Sub-basin).

Genus *Thuramminoides* Plummer 1945

Type species: *Thuramminoides sphaeroidalis* Plummer 1945.

Thuramminoides sphaeroidalis Plummer 1945; Figs. 5e, f.

1945 *Thuramminoides sphaeroidalis* Plummer, p. 218, 219, pl.15, figs. 4 (holotype), 5–10.

Remarks. The holotype of *Psammosphaera pusilla* Parr (1942, p. 106, pl. 1, fig. 6; reillustrated with SEM image by Palmieri in Skwarko 1993, pl. 1, fig. 5) has a very fine-grained wall similar to *Thuramminoides sphaeroidalis* and probably belongs within this species.

Previous illustrated Western Australian records: Crespin (1958; Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin); Belford (1968; undifferentiated Byro Group, Merlinleigh Sub-basin);

Palmieri in Skwarko 1993; re-illustration of figured specimens of Crespin 1958); Haig (2003; type section of Quinnanie Shale, Merlinleigh Sub-basin); Dixon & Haig (2004; Callytharra Formation, Byro Sub-basin).

Family Saccamminidae Brady 1884

Genus *Lagenammina* Rhumbler 1911

Type species *Lagenammina laguncula* Rhumbler 1911.

***Lagenammina* sp.**; Figs. 5g–k.

Remarks: The specimens appear similar to the Western Australian Permian tests identified by Crespin (1958, pl. 2, figs. 8, 10) as *Pelosina hemisphaerica* Chapman & Howchin. This species was based on a deflated specimen (Chapman & Howchin 1905, p. 6, pl. 12, figs. 2a, b) with short neck from the Permian of the Hunter Valley in New South Wales. Because the degree of variability, particularly in the length and degree of taper of the neck and in wall structure, among topotypes of *P. hemisphaserica* is poorly understood the present species is left under open nomenclature.

Previous illustrated Western Australian records: Crespin (1958; Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin; as *Pelosina hemisphaerica*). Haig (2003 as *Lagenammina* sp.; Quinnanie Shale, Merlinleigh Sub-basin).

Genus *Placentammina* Thalmann 1947

Type species: *Reophax placenta* Grzybowski 1898.

Placentammina ampulla (Crespin 1958); Figs. 5l–m.

1958 *Pelosina ampulla* Crespin, p. 42, 43, pl. 2, figs. 1 (holotype), 2, 3.

Previous illustrated Western Australian records: Crespin (1958, as *Pelosina*; Coyrie Formation and Bulgadoo Shale, Byro Group, Merlinleigh Sub-basin); Haig (2003, as *Placentammina* sp.; Quinnanie Shale, Byro Group, Merlinleigh Sub-basin). Dixon & Haig (2004 as *Placentammina* sp.; Callytharra Formation, Byro Sub-basin).

Family Bathysiphonidae Avnimelech 1952

Genus ***Psammosiphonella Avnimelech 1952***

Type species: *Bathysiphon arenaceus* Cushman 1927a.

***Psammosiphonella* sp.**; Figs. 5n–p.

Remarks: This species bears some resemblance to *Hyperammina* (?) *rudis* Parr (p.105, pl. 1, fig. 3, holotype; re-illustrated as a SEM image by Palmieri in Skwarko 1993, pl. 1, fig. 12). However re-examination of the holotype of Parr's species shows that it has a closed initial end with distinct proloculus. The specimens recorded here have coarsely agglutinated tubular tests open at both ends.

Previous illustrated Western Australian records: Crespin (1958 as *Hyperamminita rudis*; Callytharra Formation and Madeline Formation of Byro Group, Byro Sub-basin; Bulgadoo Shale and Wandagee Formation of Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin).

Family Hyperamminoididae Loeblich & Tappan 1984

Genus *Giraliarella* Crespin 1958

Type species: *Giraliarella angulata* Crespin 1958.

Giraliarella rhomboidalis Crespin 1958; Figs. 5q, r.

1958 *Giraliarella rhomboidalis* Crespin, p. 58, pl. 9, figs. 9 (holotype), 10.

Previous illustrated Western Australia records: Crespin (1958; upper Wandagee Formation, Bryo Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin).

Genus *Hyperamminoides* Cushman & Waters 1928b

Type species: *Hyperamminella elegans* Cushman & Waters 1928a.

Hyperamminoides elegans (Cushman & Waters 1928a); Figs. 5s, t.

1928 *Hyperamminella elegans* Cushman & Waters 1928a, p. 36, pl. 4, figs. 3, 4 (holotype).

Previous illustrated Western Australia records: Crespin (1958 as *Hyperammina*; Callytharra Formation, Merlinleigh Sub-basin; Coyrie Formation, Bulgadoo Shale, Wandagee Formation of Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin); Belford (1968 as *Hyperammina*; Lyons Group, Carrandibby Formation, Keogh Formation, Madeline Formation in subsurface Byro Sub-basin; undifferentiated Byro Group in subsurface Merlinleigh Sub-basin); Dixon & Haig (2004 as *Hyperamminoides*? sp.; Callytharra Formation, Byro Sub-basin).

Genus *Kechenotiske* Loeblich & Tappan 1984

Type species: *Hyperamminoides expanus* Plummer 1945.

Kechenotiske expansa (Plummer 1945); Figs. 5v, w.

1945 *Hyperamminoides expanus* Plummer, p. 223, 224, pl. 16, figs. 1 (holotype), 2–6.

Previous illustrated Western Australian records: Crespin (1958 as *Hyperammina*; Bulgadoo Shale, Baker Formation of Byro Group, Merlinleigh Sub-basin; ?Grant Group, Nura Nura Member of Poole Sandstone, Noonkanbah Formation, Canning Basin); Belford (1968 as *Hyperammina*; Carrandibby Formation, Callytharra Formation in subsurface Byro Sub-basin).

Kechenotiske hadzeli (Crespin 1958); Fig. 5u.

1958 *Hyperammina hadzeli* Crespin, p. 51, 52, pl. 5, figs. 6 (holotype), 7–10.

Previous illustrated Western Australian records: Crespin (1958 as *Hyperammina*; Callytharra Formation, Byro Sub-basin); Belford (1968 as *Hyperammina*; Callytharra Formation in subsurface Byro Sub-basin); Haig (2003; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin). Dixon and Haig (2004; Callytharra Formation, Byro Sub-basin).

Genus *Sansabaina* Loeblich & Tappan 1984

Type species: *Hyperammina elegantissima* Plummer 1945.

Sansabaina elegantissima (Plummer 1945); Figs. 5x, y.

1945 *Hyperammina elegantissima* Plummer, p. 222, 223, pl. 15, figs. 17 (holotype), 18–25.

Previous illustrated Western Australia records: Crespin (1958 as *Hyperammina*; Nangetty Formation, Irwin Sub-basin; Callytharra Formation, Byro Sub-basin; Callytharra Formation, Merlinleigh Sub-basin. Haig (2003; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin).

Sansabaina*? *acicula (Parr 1942); Fig. 5z.

1942 *Hyperamminoides acicula* Parr, p. 105, 106, pl. 1, figs. 4, 5, pl. 2, fig. 4 (holotype).

Previous illustrated Western Australian records: Parr (1942 as *Hyperamminoides*; "*Lingula* beds, now included in Quinnanie Shale, Byro Group, Merlinleigh Sub-basin); Crespin (1958 as *Hyperammina*; Coyrie Formation, Mallens Sandstone, Bulgadoo Shale, Cundlego Formation, Wandagee Formation, Baker Formation of Byro Group and Coolkilya Sandstone of Kennedy Group, Merlinleigh Sub-basin); Haig (2003 as *Sansabaina*?; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin).

Family Ammodiscidae Reuss 1862

Genus *Ammodiscus* Reuss 1862

Type species: *Ammodiscus infimus* L.G. Bornemann 1874 (= *Involutina silicea* Terquem 1862).

Ammodiscus erugatus Crespin, 1958; Figs. 6a, b.

1958 *Ammodiscus erugatus* Crespin, p. 66, 67, pl. 12, figs. 1 (holotype), 2, 3.

Previous illustrated Western Australian records: Crespin (1958; Noonkanbah Formation Liveringa Group, Canning Basin).

Ammodiscus nitidus Parr 1942; Figs. 6c–f.

1942 *Ammodiscus nitidus* Parr, p. 103, pl. 1, figs. 1a, b (holotype; re-illustrated as a SEM image by Palmieri in Skwarko 1993, pl. 2, fig. 26).

Remarks: Crespin (1958, p. 68, 69) noted that the initial (central) portion of the test on one side is often attached to a mica flake (e.g. Figs. 6e, f). Other specimens in the Baker Formation have initial portions attached to a large quartz grain (e.g. Fig. 6d).

Previous illustrated Western Australian records: Parr (1942; *Lingula* beds, now included within the Quinnanie Shale, Byro Group; Merlinleigh Sub-basin); Crespin (1958; Callytharra Formation, Warrawarringa Formation, Madeline Formation, Byro Sub-basin; Callytharra Formation, Coyrie Formation, Mallens Sandstone, Bulgadoo Shale, Cundlego Formation, Wandagee Formation, Baker Formation, Merlinleigh Sub-basin; Nura Nura Member of Poole Sandstone, Noonkanbah Formation, Dora Shale, Canning Basin); Belford (1968; Callytharra Formation, Keogh Formation in subsurface Byro Sub-basin; undifferentiated Byro Group in subsurface Merlinleigh Sub-basin); Palmieri in Foster *et al.* (1985; Fossil Cliff Member of Holmwood Shale, Irwin Sub-basin); Haig (2003; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin); Dixon & Haig (2004; Callytharra Formation, Byro Sub-basin).

Ammodiscus wandageeensis Parr, 1942; Figs. 6g, h.

1942 *Ammodiscus wandageeensis* Parr, p. 102, pl. 2, fig. 1 (holotype; re-illustrated as a SEM image by Palmieri in Skwarko 1993, pl. 2, fig. 27).

Previous illustrated Western Australia records: Parr (1942; *Lingula* beds, now included within the Quinnanie Shale, Byro Group; Merlinleigh Sub-basin); Crespin (1958, Quinnanie Shale, Wandagee Formation, ?Baker Formation of Byro Group, Merlinleigh Sub-basin); Belford (1968; lower Nunnery Sandstone in subsurface Byro Sub-basin); Haig (2003; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin).

Family Hormosinidae Haeckel 1894

Genus *Hormosinoides* Saidova 1975

Type species: *Hormosinoides perpastus* Saidova 1975.

Hormosinoides belfordi (Crespin 1958); Figs. 6j, k.

1958 *Reophax belfordi* Crespin, p. 60, 61, pl. 10, figs. 8–11.

Remarks: The species is transferred to *Hormosinoides* because of the straight test axis, cylindrical chambers that show a uniform, progressive increase in size and the absence of a distinct apertural neck. As based on the neotype of its type species (see Brönnimann & Whittaker 1980, p. 262–264, figs. 2, 5), *Reophax* has a more irregular test axis (slightly arcuate), more irregularly shaped chambers (irregularly pyriform) with abrupt increases in chamber size, and the final chamber drawn out into a distinct apertural neck. Rauzer-Chernousova & Reitlinger (1986) included the species in their new genus *Kunklerina* that is considered a junior synonym of *Hormosinoides*.

Previous illustrated Western Australian records: Crespin (1958, undifferentiated Byro Group, Merlinleigh Sub-basin); ?Dixon & Haig (2004 as *Reophax*? sp.; Carrandibby Formation, Byro Sub-basin).

Hormosinoides* sp. cf. *H. expatiatus (Plummer 1945); Figs. 6p, q.

cf. 1945 *Reophax expatiatus* Plummer 1945, p. 228, pl. 17, figs. 4 (holotype), 5, 6.

Remarks: This species has a much larger test that recorded by Plummer (1945) for *H. expatiatus* from the Pennsylvanian of Texas. It resembles the American species in test and chamber shape and in its coarsely agglutinated wall.

Genus *Reophax* de Montfort 1808

Type species: *Reophax scorpiurus* de Montfort 1808 (see revision and selection of neotype by Brönnimann & Whittaker 1980, p. 262–264, figs. 2, 5).

Reophax tricameratus Parr 1942; Figs. 6l–o.

1942 *Reophax tricameratus* Parr, p. 109, pl. 1, fig. 13 (holotype; re-illustrated as a SEM image by Palmieri in Skwarko 1993, pl. 3, fig. 8).

Previous illustrated Western Australia records: Parr (1942, "*Lingula* beds, now included in Quinnanie Shale, Byro Group, Merlinleigh Sub-basin); Crespin (1958, Lyons Group, Callytharra Formation, Coyrie Formation, Quinnanie Shale of Byro Group, Merlinleigh Sub-basin; Madeline Formation, Byro Sub-basin; Noonkanbah Formation, Liveringa Group, Canning Basin). Haig (2003; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin).

Family Haplophragmoididae Maync 1952

Remarks: The definition of this family follows Haig & McCartain (2010, p. 375).

Genus *Ammobaculites* Cushman 1910

Type species: *Spirolina agglutinans* d'Orbigny 1846.

Ammobaculites wandageensis Crespin 1958; Figs. 6r, s.

1941 *Ammobaculites wandageensis* Crespin, p. 74, 75, pl. 14, figs. 1 (holotype), 2, 3.

Previous illustrated Western Australian records: Crespin (1958; Coyrie Formation, Bulgadoo Shale of Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin); Haig (2003 as *Ammobaculites woolnoughi*; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin).

Family Spiroplectamminidae Cushman 1927b

Genus *Spiroplectammina* Cushman 1927b

Type species: *Textularia agglutinans* d'Orbigny var. *biformis* Parker & Jones 1865.

Spiroplectammina carnarvonensis Crespin 1958; Fig. 6t.

1958 *Spiroplectammina carnarvonensis* Crespin, p. 76, 77, pl. 22, figs. 7 (holotype), 8, 9.

Previous illustrated Western Australian records: Crespin (1958; Coyrie Formation, Bulgadoo Shale, Cundlego Formation of Byro Group, Merlinleigh Sub-basin); Haig (2003 as *Spiroplectammina eccentrica*; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin); Dixon & Haig (2004 as *Spiroplectammina eccentrica*; Callytharra Formation, Byro Sub-basin).

Family Verneuilinoididae Suleymanov 1973

Remarks. This family includes organic-cemented siliceous agglutinated species characterised by the genus *Verneuilinoides* Loeblich & Tappan. Early Permian genera that are best placed within the family include *Aaptotoichus* Loeblich & Tappan, *Digitina* Crespin & Parr, *Gaudryinopsis* Podobina and *Palustrella* Brönnimann, Whittaker & Zaninetti. These are the earliest representatives of the Verneuilinoididae.

Genus *Palustrella* Brönnimann, Whittaker & Zaninetti 1992

Type species: *Textularia palustris* Warren 1957.

Palustrella improcera (Crespin 1958); Figs. 6u–x.

1958 *Textularia improcera* Crespin, p. 78, 79, pl. 15, figs. 8 (holotype), 9.

Previous illustrated Western Australian records: Crespin (1958; Coyrie Formation, Baker Formation of Byro Group, Merlinleigh Sub-basin).

Family Trochamminidae Schwager 1877

Genus *Trochamminopsis* Brönnimann 1976

Type species: *Trochammina pusilla* Höglund 1947.

Trochamminopsis subobtusa (Parr 1942); Figs. 6y–zc.

1942 *Trochammina subobtusa* Parr, p. 109, pl. 1, figs. 14a–c (holotype; re-illustrated by a SEM image by Palmieri in Skwarko 1993, pl. 4, fig. 9).

Previous illustrated Western Australian records: Parr (1942 as *Trochammina*; "*Lingula* beds, now included in Quinnanie Shale, Byro Group, Merlinleigh Sub-basin); Crespin (1958 as *Trochammina*; Madeline Formation, Byro Sub-basin; Bulgadoo Shale, Cundlego Formation, Quinnanie Shale, Wandagee Formation of Byro Group, Merlinleigh Sub-basin; Noonkanbah Formation, Canning Basin); Belford (1968 as *Trochammina*; undifferentiated Byro Group in subsurface Merlinleigh Sub-basin); Haig (2003; Quinnanie Shale of Byro Group, Merlinleigh Sub-basin).

CONCLUSIONS

1. All Foraminifera recovered from the type section of the Baker Formation belong to organic-cemented siliceous agglutinated families and include 21 species attributed to *Psammosphaera*, *Thuramminoides*, *Lagenammina*, *Placentammina*, *Psammosiphonella*, *Giraliarella*, *Hyperamminoides*, *Kechenotiske*, *Sansabaina*, *Ammodiscus*, *Hormosinoides*, *Reophax*, *Ammobaculites*, *Spiroplectammina*, *Palustrella* and *Trochamminopsis*.

2. One new species, *Psammosphaera hockingi* n. sp. is described. Another species, *Hormosinoides* sp. cf. *H. expatiatus* (Plummer 1945), is new but represented by too few specimens to be formally described. All other species have been recorded from formations stratigraphically below the Baker Formation in Western Australia.

3. Faunal composition changes frequently through the mudstone succession in the Baker Formation. This suggests variable marine conditions in the depositional environment, for example in water depth, salinity and dissolved oxygen. The foraminiferal assemblage is consistent with brackish estuarine-like conditions in the interior sea.

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REFEREES

Those who have refereed papers and other material for the Journal recently include the following:

Ken Adkins
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Tony Cockbain
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And others who wish to remain anonymous. The Editor-in-Chief and Editorial Board of the Journal appreciate the generosity of those who review papers.